Expansion and user study of CoolVent: Inclusion of thermal comfort models in an early-design natural ventilation tool

by

Rebecca E. Rich

S.B. Massachusetts Institute of Technology (2010)

Submitted to the Department of Electrical Engineering and Computer Science

in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Electrical Engineering and Computer Science

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ABSTRACT

CoolVent, a software design tool for architects, has been improved. The work of Maria-Alejandra Menchaca-B. and colleagues has been improved to include a more robust and intuitive building and window dimensioning scheme, feedback on the validity of user inputs and thermal comfort modeling (custom, ASHRAE and adaptive). These results now allow the architect to understand how their design choices have not only affected the temperature and airflow in each of the zones of their building design but also how their design choices have affected the overall comfort throughout the zones of their building. From this, architect's can now easily understand whether their building design can be successful as a naturally ventilated building and if not, they can use the provided interface to gain insight into how their design can be modified to make their building more sustainable. A user study has been conducted to test the effectiveness of the tool.

Thesis Supervisor: Dr. Leon Glicksman

Title: Professor, Department of Architecture and Mechanical Engineering

Acknowledgements

I would like to thank my advisor, Professor Leon Glicksman, and Maria-Alejandra Menchaca-B. for their immense support and advice throughout working on the CoolVent interface. Words cannot express my gratitude for letting me work on this project, their hours of support in introducing me to CoolVent, and their feedback as I developed thermal comfort modeling for CoolVent. The comments and suggests they gave me on this thesis are invaluable.

I would also like to give special thanks to Diego Ibarra for his help in identifying the usability of CoolVent compared to other building design and thermal analysis tools and Phan Truong for her help in breaking down ASHRAE standard limits. Additionally, the support of Professor Christoph Reinhart and all of the Building Technology teaching staff and students toward completing user studies of CoolVent was greatly appreciated.

Finally, I would like to thank my family and friends for their constant support throughout this year. Without their support, none of this would have been possible. For them, I am forever grateful.

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1 Introduction

1.1 Natural Ventilation

One-sixth of energy in the Western world is utilized in operating commercial buildings [6]. Recent efforts have been focused on reducing commercial buildings' energy consumption by focusing on the energy consumed in commercial buildings for temperature control. By reducing these buildings' dependence on air conditioning, their overall energy consumption due to air conditioning could be reduced by nearly a third [6]. By additionally reducing dependence on heating and other forms of mechanical temperature control, commercial buildings' overall energy dependence could be decreased even further. We, at MIT's Building Technology Group, have turned our focus toward natural ventilation as a means to decrease commercial buildings' energy dependence.

Natural ventilation has proven to reduce dependency on air-conditioning and other forms of mechanical temperature control systems by taking advantage of pressure differences caused by a combination of wind and buoyancy forces to set up air flow through a building. Some examples of naturally ventilated buildings exist today – the San Francisco Federal Building [4], the Russia Tower (the world's largest naturally ventilated building, expected to be completed in 2012) [2], the United States Courthouse in Phoenix, and Presidio National Park, Building 1016. Furthermore, the concepts behind natural ventilation are not limited to commercial buildings but can be applied to residential buildings as well, further reducing energy consumption globally.

Natural ventilation has also been shown to improve productivity and indoor air quality by bringing increased fresh air into buildings [3,5,7].

1.2 CoolVent

Natural ventilation standards are described by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Many software tools, Computation Fluid Dynamics (CFD) tools and otherwise, have been developed to help architects design buildings based on the ASHRAE standards [9]. However, these tools require extensive understanding of both building design parameters and the physics behind the forces driving natural ventilation, while still not providing the extent of results that CoolVent can.

This required understanding often leads to disconnects between architects and engineers in the design process. In an effort to make natural ventilation more accessible for architects in the early design stages and to bridge the gap between architectural design and engineering realities, the Building Technology Group, under Professor Leon Glicksman, began designing a simulation tool, CoolVent, that requires knowledge of only early design parameters and outputs visuals that provide clear temperature and airflow analyses of the architects' designs [5].

Using Christine E. Walker's one-twelfth-size model replica of the Aldwyck building in Luton, England, Gang Tan [8] created the original version of CoolVent [7]. The resulting simulation allowed for a steady state analysis of a building design and provided results within 10-15% of the measurements from Walker's scale model. Jinchao Yuan [10] expanded the CoolVent system to include transient analyses. Following the work of Jinchao Yuan, Maria-Alejandra Menchaca-B. and colleagues expanded CoolVent into a software tool that provided a user-friendly, natural ventilation simulation tool that could run steady state and transient analyses of four key building types: single-side ventilated, cross ventilated, central atrium ventilated and side atrium ventilated [5]. The tool provided an animated visualization of the temperature and airflow throughout multiple zones of a selected building type.

I have extended the work of Maria-Alejandra Menchaca-B. and colleagues to improve CoolVent's interface for architects and in addition, have provided architects with thermal comfort modeling for the four key building types. The main inputs to the software tool have been improved to allow for more intuitive building dimensioning, feedback on the validity of user inputs and thermal comfort model selection, either based on ASHRAE standards or custom model selection. The animated visualization of the temperature and airflow has been improved, again with attention to making the interface more intuitive for architects in the early building design stages. Thermal comfort results have been presented in a new window. These results now allow the architect to understand how their design choices have not only affected the temperature and airflow in each of the zones of their building design but also how their design choices have affected the overall comfort throughout the zones of their building. From this, architects can now easily understand whether their building design can be successful as a naturally ventilated building and if not, they can use the provided interface to gain insight into how their design can be modified to make their building more sustainable. Furthermore, a user study has been conducted to truly understand the effectiveness of this tool.

2 Previous Work

2.1 Early Development of CoolVent

Gang Tan and Jinchao Yuan developed the original CoolVent simulation tool [7]. Tan (2005) used Christine E. Walker's one-twelfth-size model replica of the Aldwyck building in Luton, England, to validate his steady-state multi-zone model with CFD simulation. His work was hosted on a web-server (Figure 2.1.1) [8].

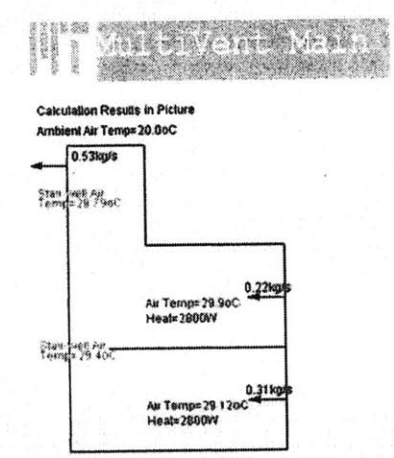


Figure 2.1.1: Tan's CoolVent Interface. The interface allowed for a steady-state, multi-zone model of a naturally ventilated building.

Jinchao Yuan (2007) expanded the work of Tan to include the transient analysis of a building design. The importance for this transient analysis lies in the possible change in external wind direction and air flow rate and the interaction with thermal mass which could result in different interactions between temperature, buoyancy and air flow within the building being designed. Yuan's transient analysis calculations are thoroughly explained and analyzed in his 2007 thesis [10].

In 2008, Maria-Alejandra Menchaca-B., under the guidance of Professor Leon Glicksman, published an extensive description of CoolVent's development after Tan and Yuan's work [5]. The interface of CoolVent at that time provided three key sequential interface windows: a general building information input window, a detailed building information input window and a results visualization window.

General Building Information Input Window

The general interface window (Figure 2.1.2) allowed architects to input basic building information. This information included: building type, the orientation of the building, building occupancy, terrain information for the building's location, and external temperature and airflow for the building's location (weather information).

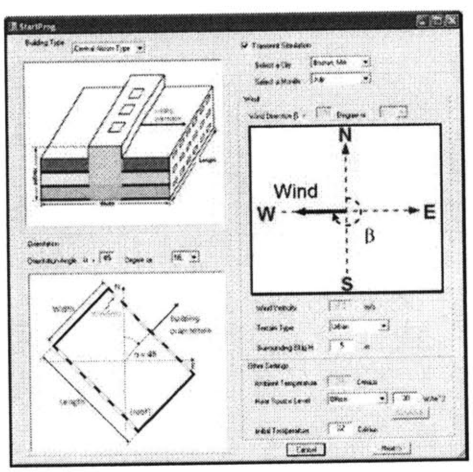


Figure 2.1.2: Menchaca-B. and colleagues' general building inputs window: This window allows users to specify building type, orientation, occupancy, terrain and weather conditions.

The program utilized a drop-down menu to select from four key building types: a building with single-sided ventilation, cross ventilation, central atrium ventilation or side atrium ventilation (Figure 2.1.3). After selecting the building type, architects could define the orientation of the building type using one of the eight cardinal and intermediate directions.

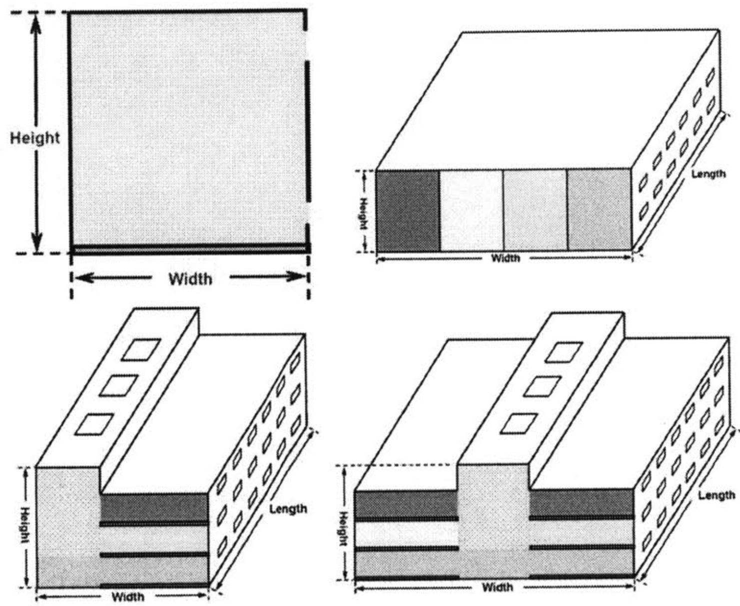


Figure 2.1.3: Menchaca-B. and colleagues' CoolVent simulation tool analyzes four key building types: [Top Left] single-side ventilated, [Top Right] cross ventilated, [Bottom Left] central atrium ventilated and [Bottom Right] side atrium ventilated.

Next, building occupancy type can be defined (using a drop-down menu with a heat load density text input field) as: residential ($20W/m^2$), office ($30W/m^2$), educational ($40W/m^2$), or as any arbitrary heat load density.

After defining the building occupancy expectations for the design, architects defined the terrain information (urban, rural or airport, all yielding suggested average height of surrounding buildings) for the building's location as well as the expected weather conditions, both inputs related to the air flow and temperature external to the building being designed. After deciding on the terrain type, architects would then decide whether they wished to run a steady-state or twenty-four hour, transient analysis on their building design. For steady-state analyses, wind speed and direction as well as the ambient temperature would also be inputted. For transient analyses, weather information (average temperature, wind speed and direction for each our of the day) for one of ten major locations: Atlanta, Boston, Charlotte, Chicago, Houston, Los Angeles, Miami, Puerto Rico, San Francisco or Seattle would also be selected.

Detailed Building Information Window

The next interface window (Figure 2.1.4) allowed architects to input detailed building information. This information included: building dimensions, window opening characteristics, thermal mass descriptions and window control strategies.

The first detailed specifications that could be specified using this interface window were the building dimensions. These specifications, all entered using text fields, included: the number of floors in the building design, the occupational floor height, length and width, the roof height, and the atrium width (for the central and side atrium building types).

Next, window opening characteristics of the building design were specified with glazing area and window openings. For the single-sided ventilation building type, architects would specify the vertical location of the window; for the central and side atrium building types, the roof opening area and for the cross ventilation, the internal door area. These inputs were again established using text fields.

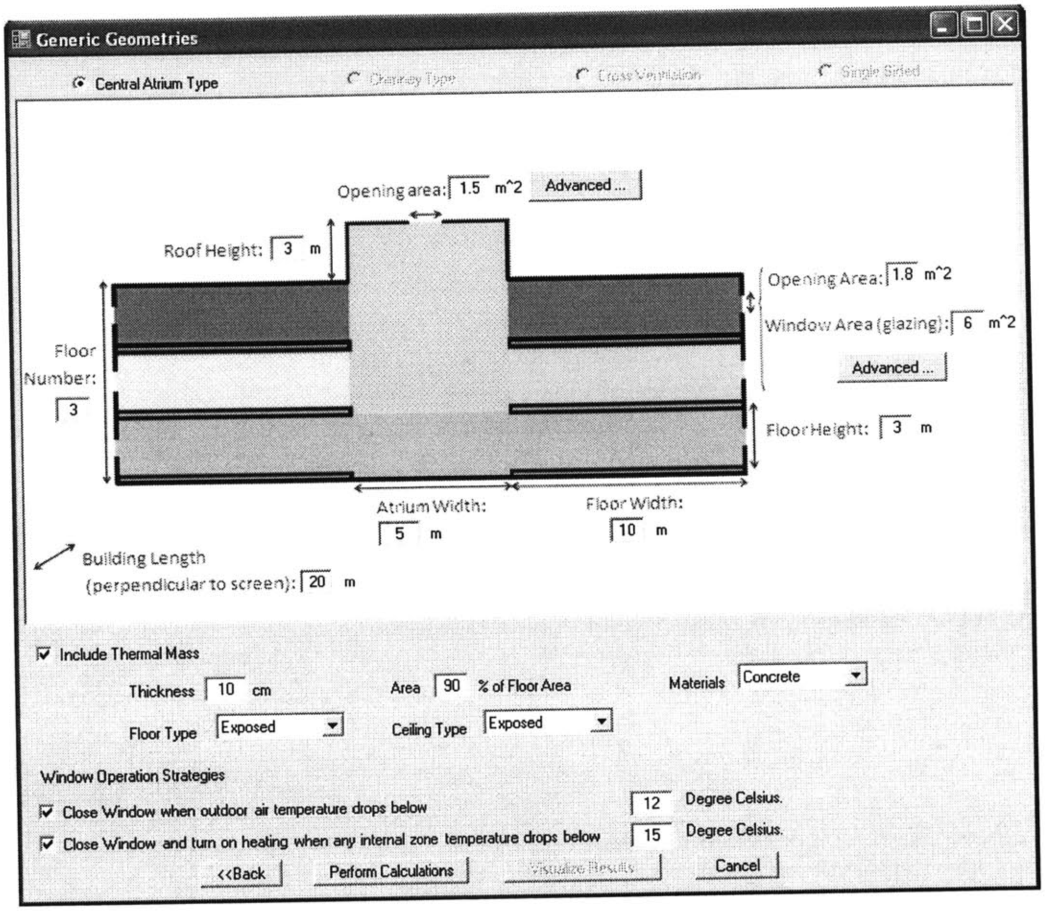


Figure 2.1.4: Menchaca-B. and colleagues' detailed building inputs window. This window allows users to define building dimensions, window opening characteristics, thermal mass descriptions and window control strategies.

The optional thermal mass description inputs allowed the specification of slab thickness, occupational surface area percentage, building materials, floor type and ceiling type using text fields and drop-down menus.

Finally, architects could define window closing strategies for their building's design. With these strategies, temperature thresholds at which the windows would be closed and heating systems would be turned on could be specified. These strategies were activated using check-boxes and text field temperature threshold entries.

Results Visualization Window

After entering general and detailed information about their building design, the results of the simulation were displayed in the visualization window (Figure 2.1.5). This visualization window provided a color-coded description of the temperatures throughout the zones of the designed building as well as air flow rates and directions at its windows.

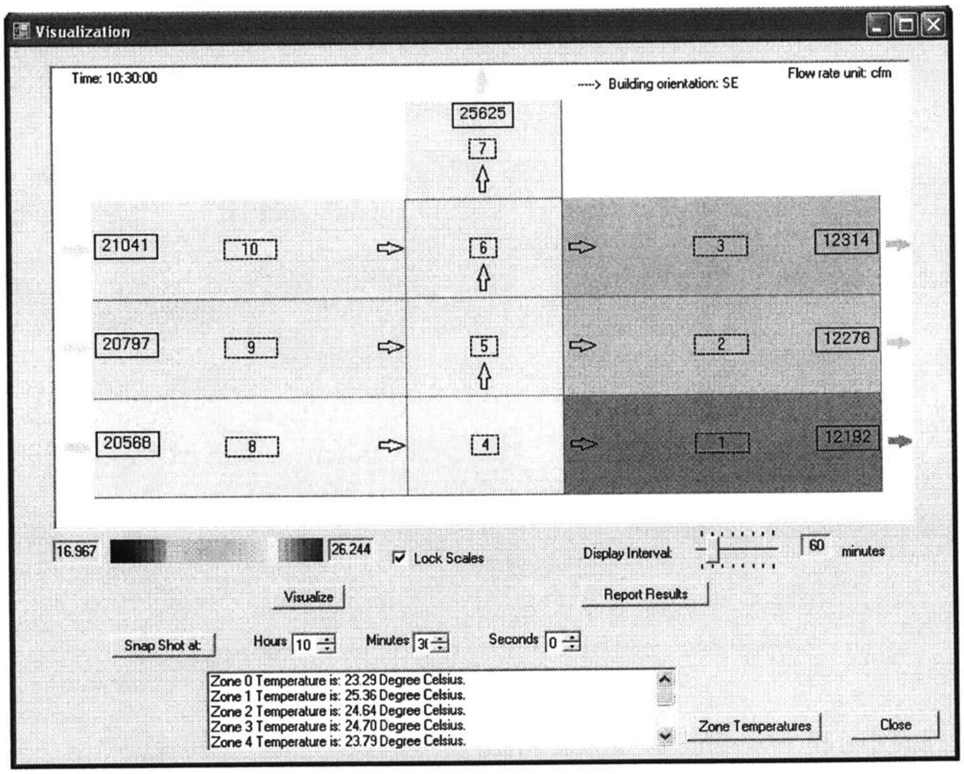


Figure 2.1.5: Menchaca-B. and colleagues' CoolVent visualization window allows users to see a zone-by-zone temperature and airflow analysis of their building design.

Detailed plots of different zones temperatures throughout a twenty-four hour, transient analysis could be accessed through a scroll-bar menu (Figure 2.1.6), and a result snap shot could be viewed upon button request from the use-r.

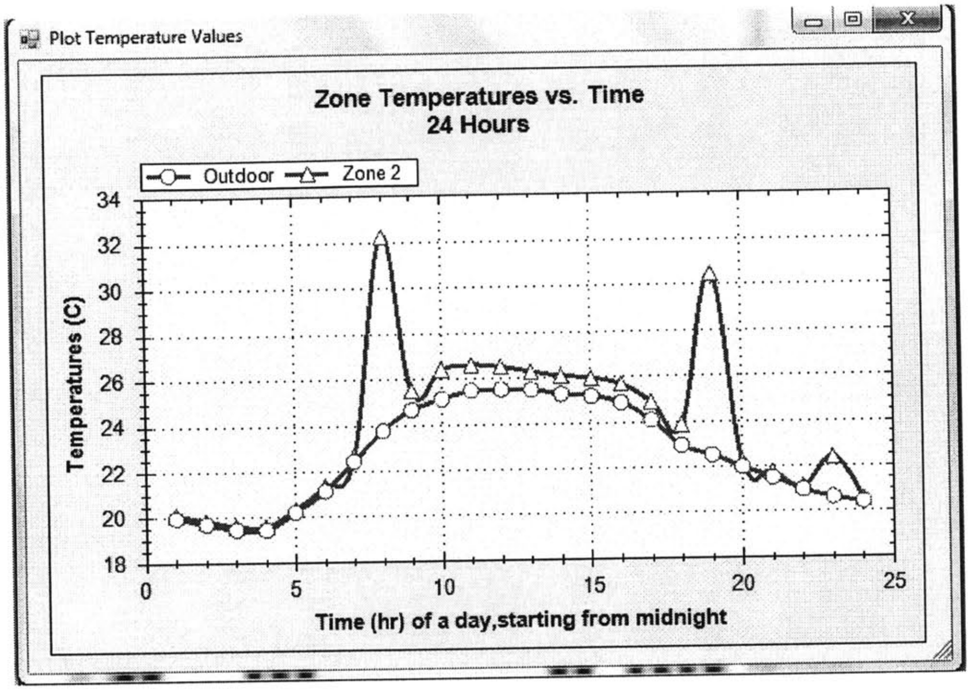


Figure 2.1.6: Menchaca-B. and colleagues' zone-by-zone, transient visualization option. This window allows users to see a specific zone's temperature variation with respect to the outdoor temperature variation.

Transient simulations could also be visualized via an animation of the temperatures throughout the twenty-four hour simulation time period. Alternatively to the visualization window, results could be viewed in a text file.

2.2 CoolVent, August 2010

The work of Maria-Alejandra Menchaca-B. and colleagues has yielded much improvement to CoolVent since the publication of the 2008 SimBuild description. The three sequential interface windows of the 2008 version of CoolVent have evolved into a six tab interface (Figure 2.2.1) that runs under a C# interface in Microsoft Visual Studio and Java calculations. The interface also features two drop down file menu options: a unit selection drop down menu for switching between SI and English units and a save/load/quit menu. Additionally, there is a side scenario bar.

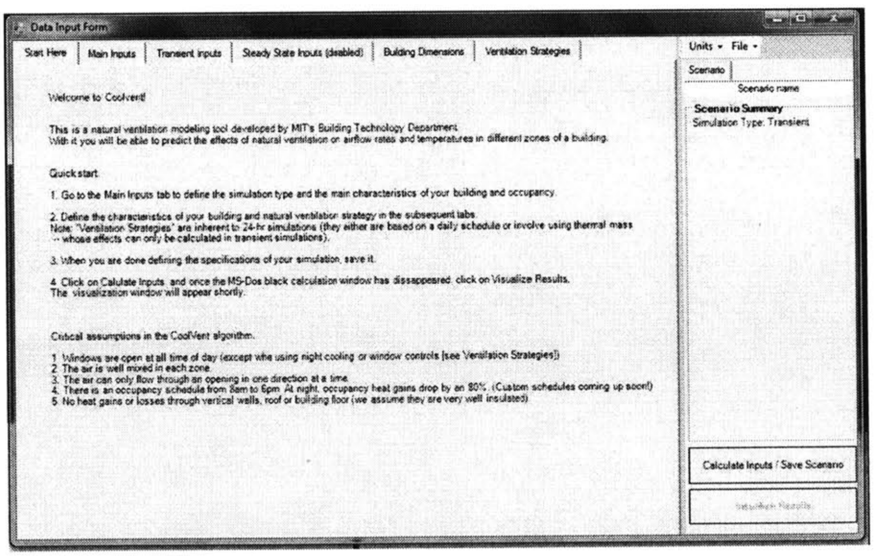


Figure 2.2.1: CoolVent's start screen (or tab) provides a welcome screen, quick start guide and critical assumptions list for the CoolVent interface.

The start screen (or tab) for the current CoolVent interface provides a welcome screen for the user along with a quick start guide and the critical assumptions underlying the CoolVent calculations.

As detailed in the quick start guide, CoolVent's base interface begins with the main inputs tab (Figure 2.2.2). Within the main inputs tab, architects decide whether to run a steady-state or transient analysis of a building design. They also specify general building details starting with the building type using a drop down menu. Similar to the 2008 version of the system, the simulation allows for the analysis of four building types: central atrium, chimney type, cross ventilation and single sided ventilation. The chimney type building corresponds to the side atrium building type of the 2008 version of CoolVent. Based on the building type selection, the interface will display a three-dimensional model of the design's layout.

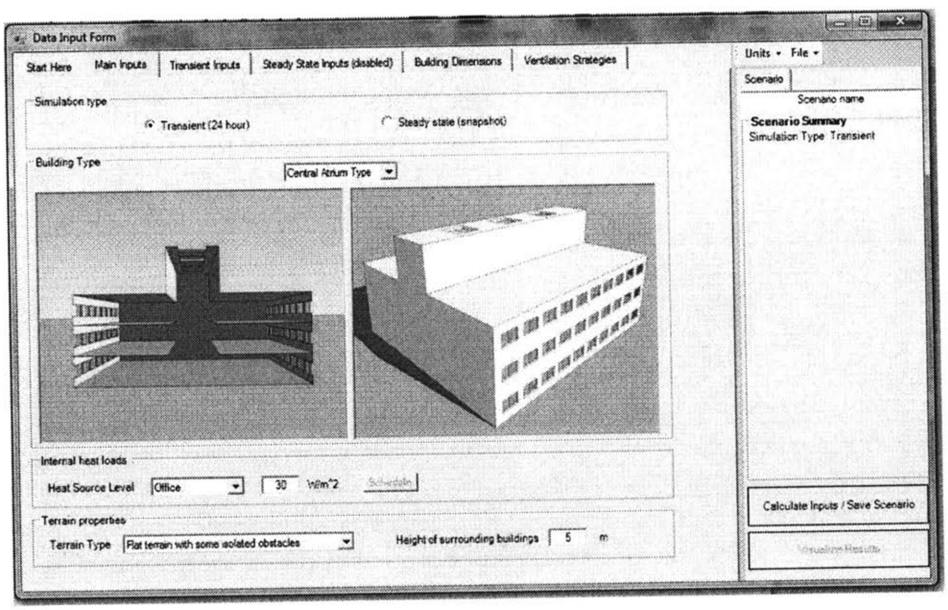


Figure 2.2.2: CoolVent's main inputs tab allows a user to specify simulation type, building type, internal heat loads and terrain properties.

After specifying building type, architects are asked to specify the expected internal heat loads for their building by selecting from a drop down menu: zero source (0W/m^2), office (30W/m^2), residential (20W/m^2), or educational (40W/m^2) internal heat loads. If a zero source internal heat load is selected, expected occupied hours and off-peak equipment load fractions can be specified for the design.

Finally, architects define the terrain properties for the building design to determine obstructions to external wind flow using a drop-down menu. Choices include: flat terrain with some isolated obstacles, rural area with low buildings, center of a large city, or urban, industrial or forest area. The expected height of the buildings surrounding the design is then specified.

The next stage in the simulation is to define transient or steady state inputs. If architects select a transient analysis, they will select the transient inputs tab (Figure 2.2.3). This tab prompts them to input weather data for the location where the building will be constructed using a drop down menu. CoolVent's locations include: Atlanta, Boston, Charlotte, Chicago, Houston, Los Angeles, Miami, New Orleans, New York City, Puerto Rico, San Antonio or Seattle. Unlike the 2008 version of CoolVent, architects also have the option to select "Other" for the building location. With this option, they can browse their computer system for the weather data files (*.epw) of any location. After selecting the location for their designed building's construction, they are prompted to choose a month for the transient analysis weather data to be taken from.

The graph in the lower left-hand corner of the transient inputs tab will reflect the outdoor temperature, wind velocity, and relative humidity data for a typical day in the selected city during the selected month. Additionally, the wind chart in the lower right-hand corner of the transient inputs tab will reflect the expected wind conditions for the location and month selections.

Under the transient inputs tab, architects are also prompted to input information regarding the orientation of the building façade and can select from cardinal and intermediate diretons using a drop down menu. The building plan diagram will update drawing orientation with respect to due north on the transient inputs tab.

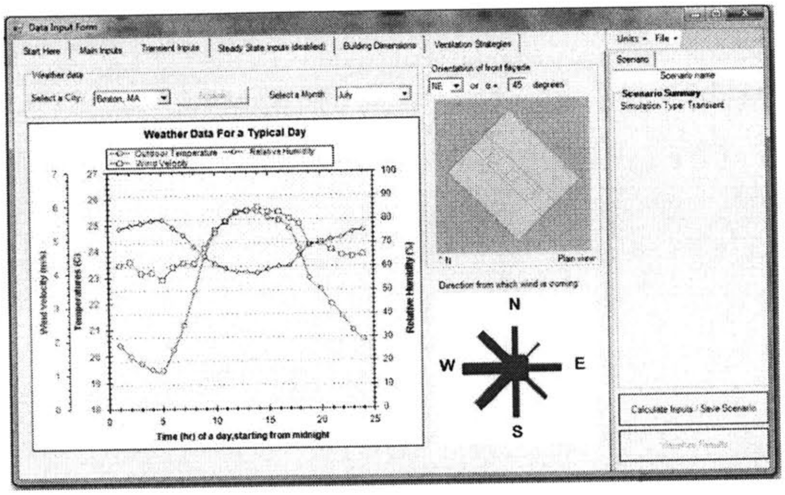


Figure 2.2.3: CoolVent's transient inputs tab allows users to select location and weather data as well as the orientation of the building's façade. The two plots illustrate temperature, wind velocity, relative humidity and wind direction based on the selected location.

Alternatively, if architects chose to run a steady state analysis, they will select the steady state inputs tab (Figure 2.2.4). This tab prompts for the design's temperature, wind and orientation settings, independent of weather data files. Architects can use text field inputs to enter temperature settings – ambient and initial temperatures, and similarly to the transient analysis tab, can specify the orientation of the building façade using a drop-down menu to select between the cardinal and intermediate directions. The building plan view changes orientation with respect to the user's building orientation selection.

After specifying the temperature and orientation characteristics behind steady state analysis, wind settings should be specified. Using a drop-down menu, architects can select the wind direction external to the designed building as one of the cardinal or intermediate directions. Further, using a text field input, they can define the wind's velocity.

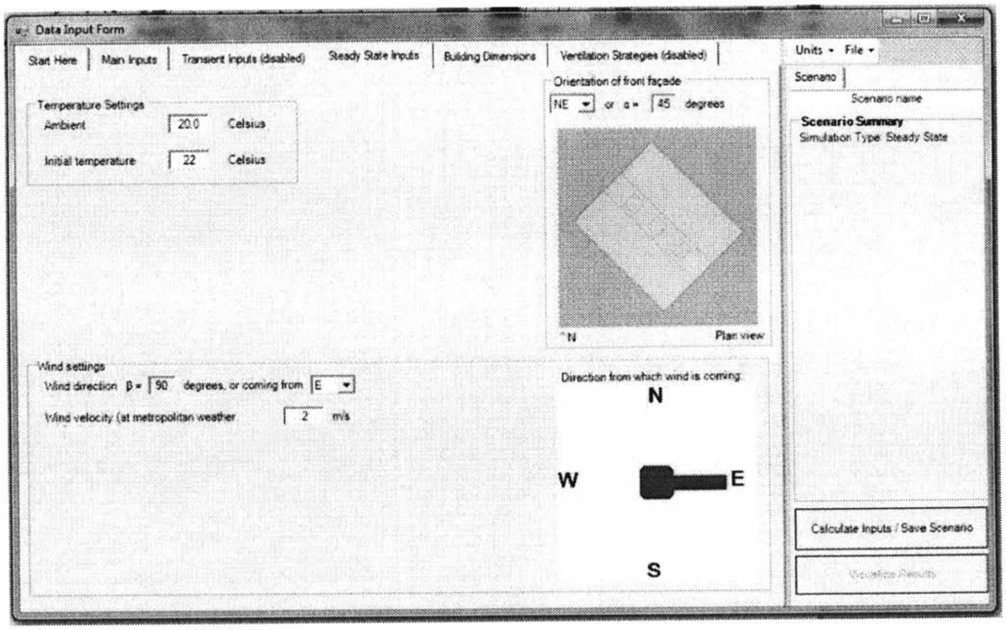


Figure 2.2.4: CoolVent's steady state inputs tab allows users to establish temperature settings, wind settings and building façade orientation.

After entering transient or steady state inputs, building dimensions can be specified (Figure 2.2.5). Using the Building Dimensions tab, architects can define these parameters using a side view of the design plan and text field inputs. CoolVent prompts for the number of floors in the building design in addition to the floor width, floor length, roof height, floor height, floor length, and atrium width depending on the selected building type.

After specifying building dimensions, architects can specify window dimensions. Top window size, the side window size, and the side glazing area (or the area subject to solar heat load) are specified using text fields. Information regarding the top and side window specifications can be specified via two buttons at the bottom of the tab. The top window specification button, when checked, creates a separate window for entering the window opening area, number of the windows, and spacing distance for the top windows (Figure 2.2.6). Similarly, the side window specification button, when clicked, prompts architects (using a separate window) for the area of each lower window, the area of each upper window, the total number of windows, the height of the lower window and the height of the upper window (Figure 2.2.7).

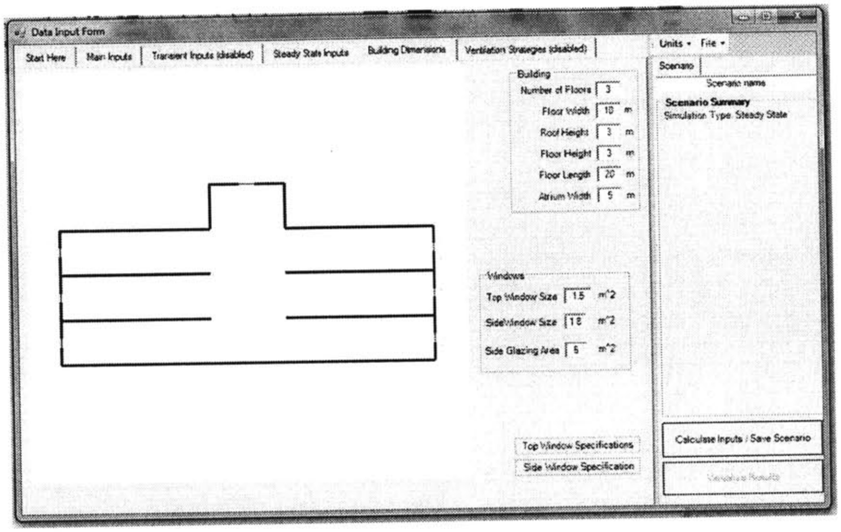


Figure 2.2.5: CoolVent's building dimensions tab allows users to specify detailed building information – building dimensions and window specifications.

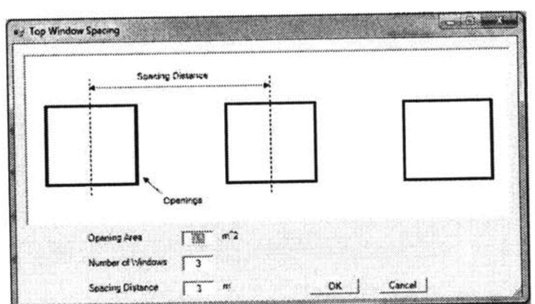


Figure 2.2.6: CoolVent's top window spacing interface allows users to specify the opening area and spacing distance of the top windows, as well as how many top windows are included in the building design.

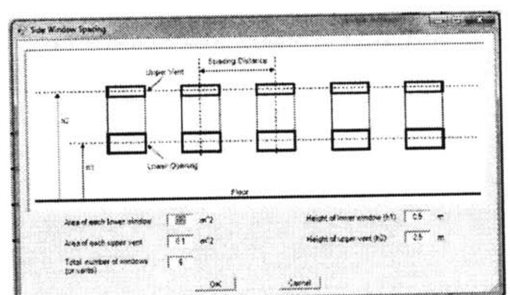


Figure 2.2.7: CoolVent's side window spacing interface allows users to specify the area and height of the lower and upper parts of the side windows as well as the number of side windows.

Once detailed building parameters are defined, architects can specify ventilation strategies via CoolVent's Ventilation Strategies tab (Figure 2.2.8). Similar to the 2008 version of CoolVent, thermal mass specifications can be selected and window operation can be controlled. The user can select thermal mass options using a check box selection. If thermal mass specifications are selected, architects are prompted to enter information about floor slab thickness and exposed floor area percentage using text fields. Additionally, drop-down menus can be used to specify information about floor slab material (concrete, brick or steel), floor type (exposed, carpeted or raised) and ceiling type (exposed or suspended).

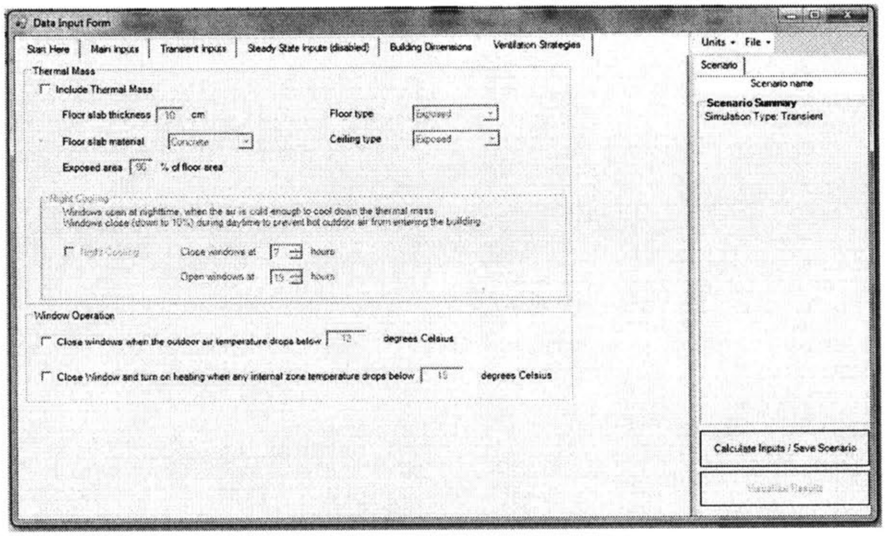


Figure 2.2.8: CoolVent's ventilation strategies tab allows users to input thermal mass specifications as well as night cooling and window operation options.

If the thermal mass option is selected, architects also have the option to specify the night cooling option. The night cooling option allows the windows to be controlled, allowing cool air to flow into the building at night and preventing warm air from flowing into the building during the day.

Finally, architects can select window operation options. Windows can be designed to close at some threshold temperature or so that the windows close and the heat turns on at some other threshold temperature during cool weather.

Once architects specify their design under the six tabs, they can visualize the results of the steady state or transient simulation of their building design by selecting the "Calculate Scenario / Save Scenario" button at the lower right-hand corner of the interface.

After waiting a few seconds for the results to process and selects "Ok" to the prompt (Figure 2.2.9), they can select the "Visualize Results" button at the lower right-hand corner of the CoolVent interface.

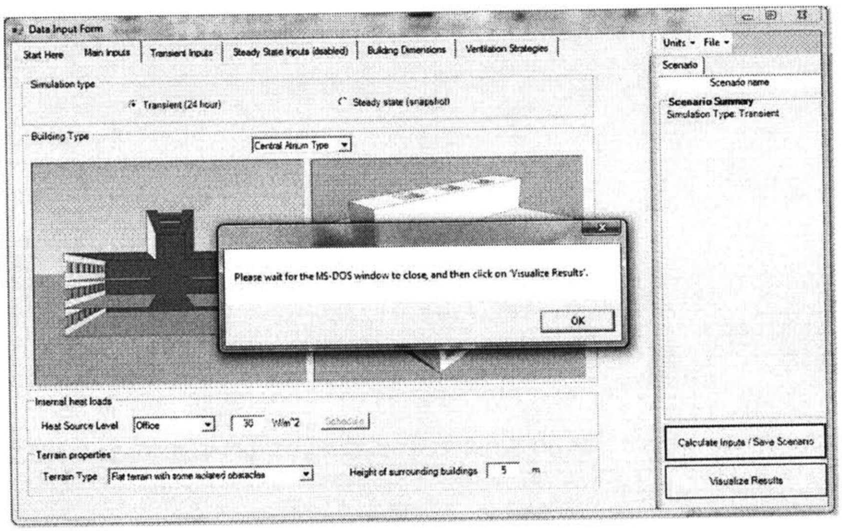


Figure 2.2.9: CoolVent's interface will prompt a user to wait for the MS-DOS window to close, signifying the completion of the simulation calculations. After the calculations are complete and a user selects the "Visualization Results" button in the lower right-hand corner of the interface window to see the simulation results.

They will then be greeted with the temperature and air flow results for their building design. For steady state analyses, they will see a snap-shot of the expected temperatures and air flows throughout the design layout (Figure 2.2.10), and they will also have the option to view the results in a text file by selecting the "View Hourly Report" button (Figure 2.2.11).

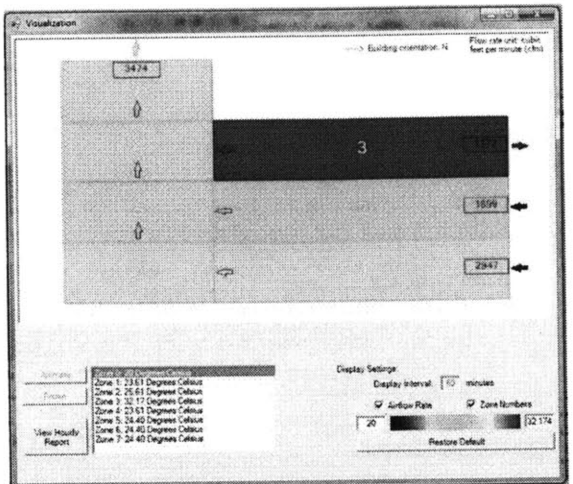


Figure 2.2.10: CoolVent's steady-state visualization window allows a user to see a color-coded snap-shot of the building design's temperature and airflow characteristics by building zone.

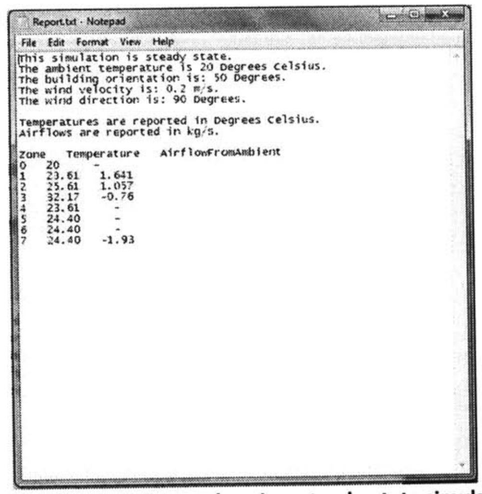


Figure 2.2.11: A user can also view steady-state simulation results as a text file.

For transient analyses, they will see a twenty-four hour analysis of the expected temperatures and airflows throughout the design layout (Figure 2.2.12). The transient analysis results allow users to scroll through the building zones by hour and also allow users to view the temperature variations by zone throughout the full twenty-four hour period graphically (Figure 2.2.13).

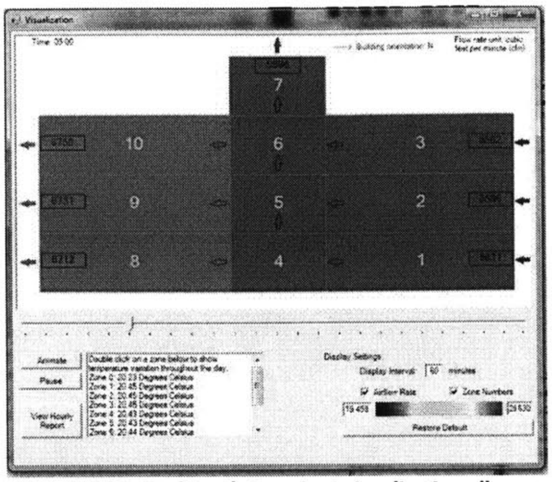


Figure 2.2.12: CoolVent's transient visualization allows a user to see a color-coded diagram of the building design's temperature and air flow characteristics by building zone throughout a twenty-four-hour period. A user can also view an animated visualization of these results.

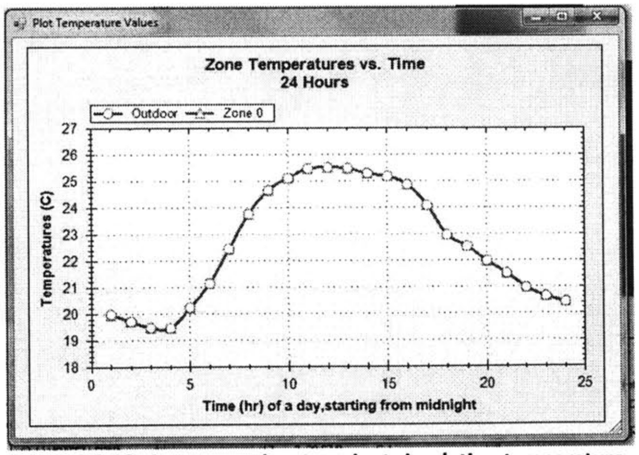
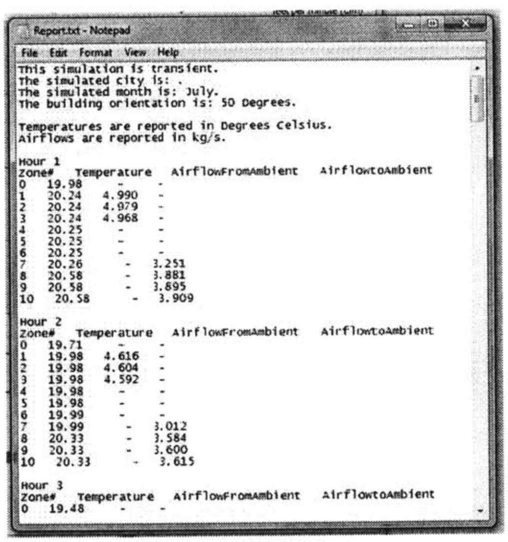


Figure 2.2.13: A user can view transient simulation temperature results by zone for the entire twenty-four-hour period with respect to outdoor temperatures.

Additionally, architects can view an animation of the full twenty-four hour period and can pause the animation at a time of interest. As with the steady state analysis results, a text file summary of results can be viewed by selecting the "View Hourly Report" button (Figure 2.2.14).



Report.txt - Notepad

File Edit Format View Help

```
This simulation is transient.
The simulated city is: .
The simulated month is: July.
The building orientation is: 50 Degrees.

Temperatures are reported in Degrees Celsius.
Airflows are reported in kg/s.

Hour 1
Zone#   Temperature   AirflowFromAmbient   AirflowtoAmbient
0   19.98    -     -
1   20.24   4.990  -
2   20.24   4.979  -
3   20.24   4.968  -
4   20.25    -     -
5   20.25    -     -
6   20.25    -     -
7   20.26     -   3.251
8   20.58     -   3.881
9   20.58     -   3.895
10   20.58     -   3.909

Hour 2
Zone#   Temperature   AirflowFromAmbient   AirflowtoAmbient
0   19.71    -     -
1   19.98   4.616  -
2   19.98   4.604  -
3   19.98   4.592  -
4   19.98    -     -
5   19.98    -     -
6   19.99    -     -
7   19.99     -   3.012
8   20.33     -   3.584
9   20.33     -   3.600
10   20.33     -   3.615

Hour 3
Zone#   Temperature   AirflowFromAmbient   AirflowtoAmbient
0   19.48    -     -
```

Figure 2.2.14: A user can also view transient simulation results as a text file.

3 Base Interface

CoolVent's base interface was a constant focus for development. Intuitive results for a building design's temperatures, air flows and comfort could never be developed if architects did not understand how to specify their buildings' designs using CoolVent. In developing CoolVent's base interface, eight key attributes' user interface and technical / software issues were addressed, as outlined in Table 3.1.

Main Inputs Tab

The first of these eight attributes – CoolVent's Main Inputs Tab - allows architects to specify simulation type (transient or steady state), building type (Central Atrium, Chimney, Cross Ventilation, Single Sided Ventilation), internal heat loads and terrain properties (Figure 3.1). Although Cool Vent's main input tab has not visually changed, the operation of this tab has. To improve the user interface, only tabs relevant to steady state or transient analyses, respectively, were allowed to be visible. In previous versions of CoolVent, all tabs remained visible regardless of simulation type and if an incorrect tab was selected, a warning box would appear. Now, when an architect selects a transient analysis from the Main Inputs Tab, only the Transient Inputs Tab, the Building Dimensions Tab, the Ventilation Strategies Tab and the new Thermal Comfort Tab are visible (in addition to the Start Screen Tab and the Main Inputs Tab). Conversely, if an architect selects a steady state analysis type from the Main Inputs Tab, only the Steady State Inputs Tab and the Building Dimensions Tab are visible (in addition to the Start Screen Tab and the Main Inputs Tab). By restricting the visibility of tabs based on analysis type

Attribute	Brief Description	User Interface Issue	Technical / Software Issue
Main Inputs Tab	Allows a user to specify simulation type, building type, internal heat loads and terrain properties.	• Only tabs relevant to Steady State and Transient analyses, respectively should be visible for a user to select.	• Added input error checking for Heat Load Density and Surrounding Building Height inputs.
Steady State Inputs Tab	Allows users to establish temperature settings, wind settings and building façade orientation.	• Added input for a humidity metric for comfort analysis.	• Added input error checking for Ambient Temperature, Initial Temperature, Relative Humidity and Wind Velocity inputs.
Transient Inputs Tab	Allows users to select location and weather data as well as the orientation of the building's façade.	--	• Addition of Arlington, VA (Washington D.C.) and San Francisco, CA. • Ensure that city name is updated appropriately and not as the city file name. • Ensure that building orientation is updated on visualization page.
Building Dimensions Tab	Allows users to specify detailed building information – building dimensions and window specifications.	• Updated building drawing to pseudo-3D drawing • Updated window calculation method so that it is more intuitive for architects • Updated dimension names so that they are more intuitive for architects.	• Building dimension input scheme changed to minimize program variables and GUI movement. • Added input error checking for any building or window dimension inputs.
Top Window Spacing Interface	Allows users to specify the opening area and spacing distance of the top windows, as well as how many top windows are included in the building design.	• Removed in place of a window calculator	--
Side Window Spacing Interface	Allows users to specify the area and height of the lower and upper parts of the side windows as well as the number of side windows.	• Removed in place of a window calculator	--
Ventilation Strategies Tab	Allows users to input thermal mass specifications as well as night cooling and window operation options.	--	• Correct initial update of night cooling open and close hours. • Added input error checking for Floor Slab Thickness, Exposed Area Percentage and Close Window Temperature Threshold inputs.
Calculate / Visualize Buttons	Allows users to move from the base interface to the simulation results and Visualization window.	--	• Warning that all tabs should be visited before calculating. • Warning if any inputs are invalid before calculating.

Table 3.1: Base interface attributes.

selection, the software prevents inappropriate tabs from being selected, and it also prevents parameters irrelevant to the analysis type from being entered. From a technical / software perspective, error prevention was added for the Heat Load Density and Surrounding Building Height inputs. Previous to this modification, if an invalid value was inputted into either of these text fields, for example a letter instead of a number, the whole program would crash. Now, if an invalid input is typed into either of these text boxes (including a lack of input), the box will turn red as a warning to the user that the input is valid and the program will continue to run.

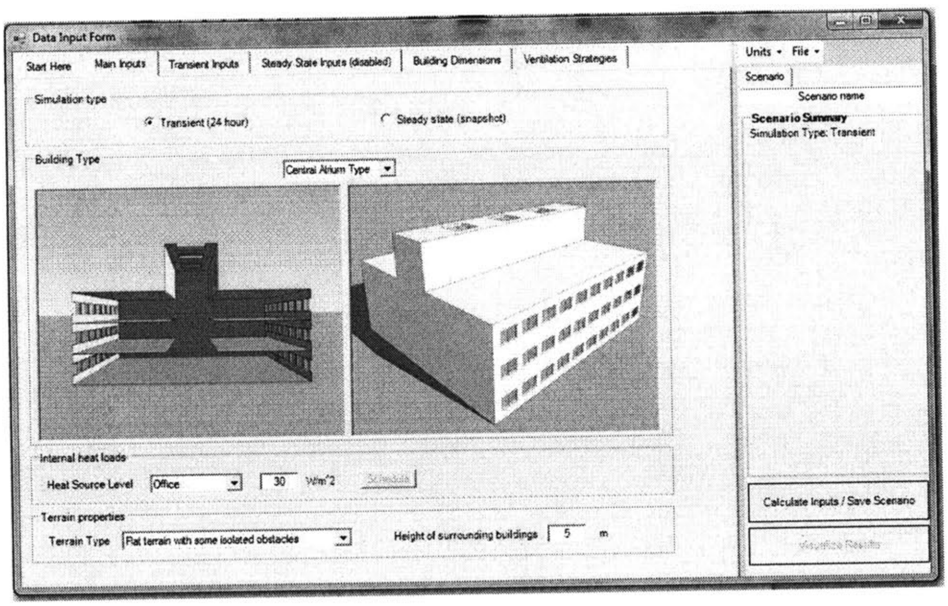


Figure 3.1: CoolVent's main inputs tab allows architects to specify simulation type, building type, internal heat loads and terrain properties.

Steady State Inputs Tab

CoolVent's Steady State Inputs Tab saw minor modifications (Figures 3.2 and 3.3). To facilitate thermal comfort analysis for steady state simulations, the previous Temperature Settings input group was renamed "Weather Settings," and a relative humidity input was added to the previously existing inputs. As with the main inputs tab, error prevention was added to the Steady State Inputs Tab. The ambient temperature, initial temperature, relative humidity and wind velocity inputs were modified so that if a non-number is typed into the any of the text boxes (or the backspace is hit, leaving the text box empty), that box will turn red as a warning of an invalid input. Additionally, the relative humidity input was restricted to valid percentage inputs on the range of 0-100.

CoolVent's Steady State Input Tab Comparison

Previous

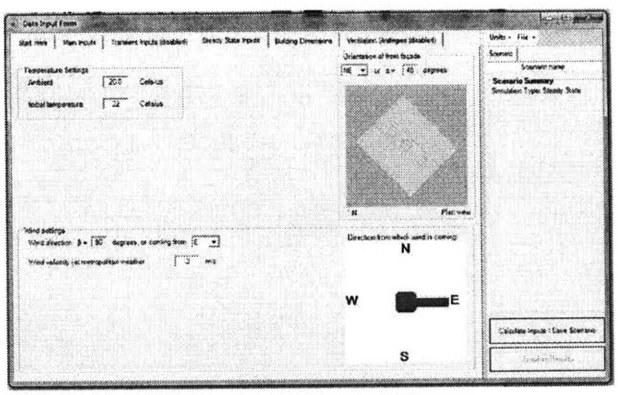


Figure 3.2: CoolVent's steady state inputs tab allows architects to establish temperature settings, wind settings and building façade orientation.

Current

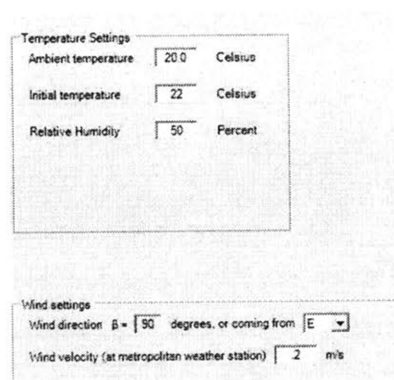


Figure 3.3: CoolVent's current steady state input tab has been modified to include a relative humidity input as well as error prevention for all text inputs.

Transient Inputs Tab

CoolVent's Transient Inputs Tab allows architects to select the location of a building design as well as weather data and the orientation of the building's façade. Although Cool Vent's transient input tab has not visually changed, there were several technical / software concerns with the tab.

The first change made to the Transient Inputs Tab was the addition of Arlington, VA (Washington D.C.) and San Francisco's weather data to the City selection drop down menu. Further, the city name and city file name were not always tracking the correct values for later results text files. These inputs were updated so that the city name and file name are always up to date, and if "Other" is selected from the drop down menu, the city name reverts to the city file name. Finally, the building orientation was not updating to the later Visualization window for the results, so the building orientation inputs were updated to always correctly read from user inputs.

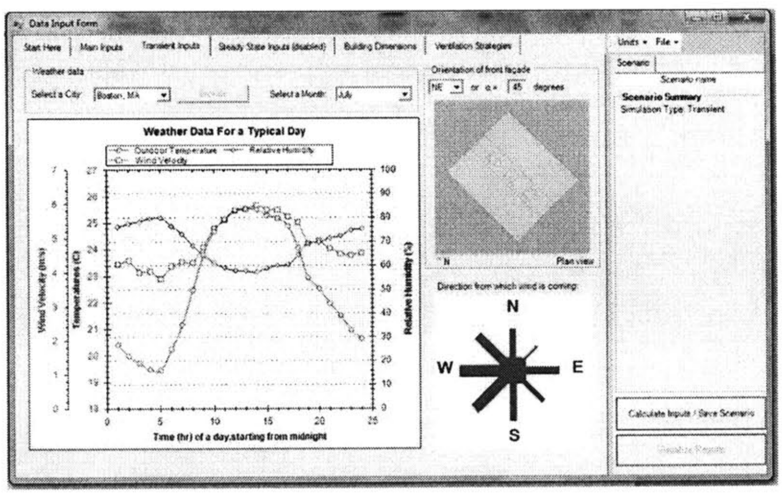


Figure 3.4: CoolVent's transient inputs tab allows users to select location and weather data as well as the orientation of the building's façade. The two plots illustrate temperature, wind velocity, relative humidity and wind direction based on the selected location.

Building Dimensions Tab

CoolVent's Building Dimension Tab allows architects to specify detailed building information – building dimensions and window geometries. Extensive work has been put into improving both the user interface and technical / software components of this tab.

The user interface has been updated from the previous two-dimensional drawings to pseudo three-dimensional drawings (Figure 3.5). This modification allows users to see a direct correlation between all of the building dimension inputs and the physical building design. Whereas before a modification in floor length would not be visible in the building design drawing, now a user can see the depth of the building increase with increases in the floor length input. These same building dimensions (number of floors, floor (bay) width, floor height, floor length, chimney width, roof height and number of sections) were also repeatedly renamed until an intuitive naming convention for architect's was found. Additionally, the software originally contained four separate building dimensions variables, one for each building type, resulting in an excessive number of variables. This scheme was modified to allow for only seven building dimension variables that would be enabled to modify only if they applied to the selected building type. This change allowed for a more fluid interface. Additionally, input error prevention was added to all of these building dimension inputs, so that if an invalid input was entered, the input box would turn red and the automatic updating for the building drawing would stall until all building dimensions are valid.

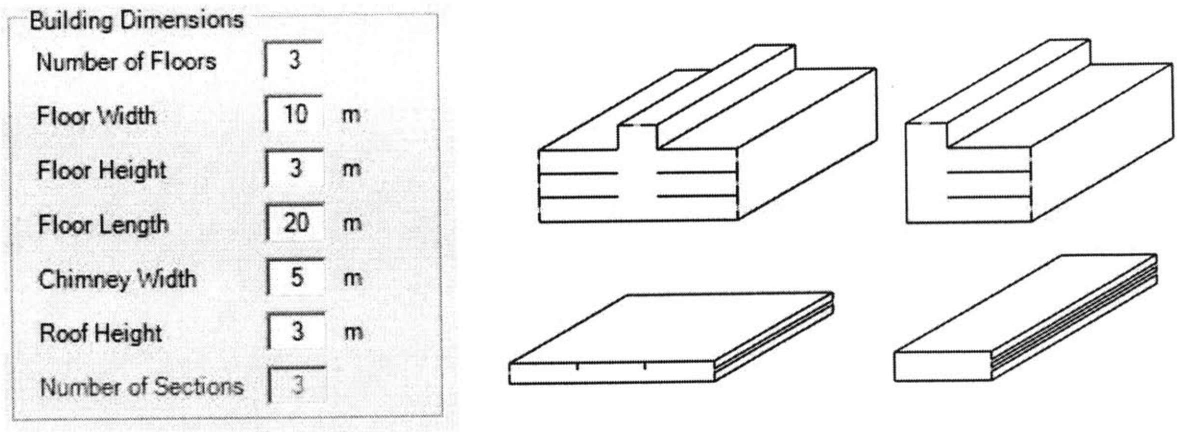


Figure 3.5: Pseudo Three-Dimensional Building Drawings. Architects can now see a direct correlation between all of the building dimension inputs and the physical building design. The drawings will automatically update to user inputs provided they are valid.

Beyond the scope of the building dimension inputs, the window dimension inputs have been updated. Instead of having a "Top Window Specifications" and a "Side Window Specifications" button to specify building window sizes, the building dimensions tab now has two calculator buttons (Figure 3.6). These buttons now intuitively link up to the previous window associated with the two specification buttons to make it more intuitive that the goals of these two windows is to help calculate the window areas.

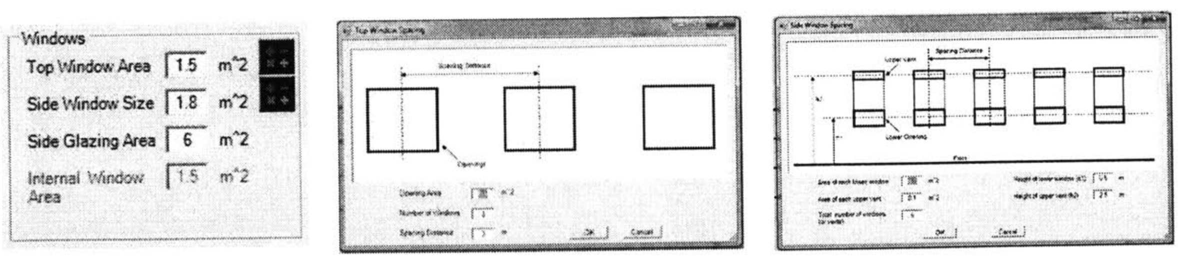


Figure 3.6: CoolVent's New Window Dimensions. Two calculator buttons now allow architects to calculate top window and side window specifications.

Ventilation Strategies

CoolVent's Ventilation Strategies Tab's user interface was not modified; however, a few technical / software modifications were made to the tab. First, the night cooling window opening and closing hours were updated. Originally, the night cooling would only work if you changed these inputs; the initial values were not being updated into the program and instead were both being initialized at 0 hours. The inputs were updated so that the defaults were stored. Additionally, as with the other base interface tabs, input error prevention was added to all inputs of the visualization strategies tab (Floor Slab Thickness, Exposed Area Percentage and Close Window Temperature Threshold Inputs).

Calculation and Visualization

CoolVent's Calculate/Inputs and Save Scenario to Visualization process has been modified in two major ways – the addition of a check for the user visiting all CoolVent tabs before calculating a building design's simulation results and the addition of a check for invalid inputs in the CoolVent base interface. Previously, when attempting to calculate results for a building design, a window would pop-up with the following warning, "Please wait for the MS-DOS window to close, and then click on 'Visualize Results'" (Figure 3.7). This window was design to encourage users to wait for the Java calculations to finish running before attempting to view simulation results.

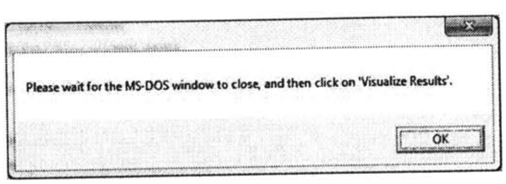


Figure 3.7: Wait for MS-DOS Window: A window warning architects to let Java finish calculating simulation results before they attempt to visualize results.

Now, an additional window will appear if all of the CoolVent tabs have not been visited (Figure 3.8). This warning is especially important for new CoolVent users, as without visiting all of CoolVent's tabs, they cannot guarantee that they have a full understanding of program capabilities nor can they guarantee that they have inputted the entirety of parameters necessary to specify their building's design. By having a yes/no selection on this window, fluent users are allowed to continue to calculations, as they may not need to visit all of the CoolVent tabs to properly specify their building's design.

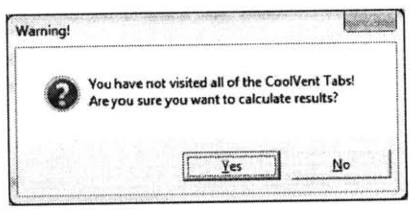


Figure 3.8: "You Have Not Visited all of the CoolVent Tabs!" Warning

Furthermore, an additional window will appear if any invalid inputs have been entered into CoolVent's base interface (Figure 3.9). The window warns users, "Some of your inputs are invalid: Look for Red Boxes! Are you sure you want to continue?." This window completes the error checking methodology for the base interface, preventing the program from crashing when invalid inputs are entered thus increasing overall program stability.

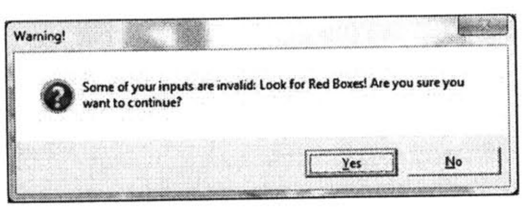


Figure 3.9: Invalid Inputs Warning Window: This window completes the error checking methodology for the base interface, preventing the program from crashing if the user selects "No" from this window and corrects their invalid inputs.

4 Visualization Window

With CoolVent's base interface improved, the visualization window, a window for presenting temperature and air flow results for a building design, was developed with focus toward four key attributes: the twenty-four hour transient animation building drawing, the transient simulation animation controls, the transient and steady state simulation display setting controls and the transient simulation thermal comfort modeling results access (Table 4.1).

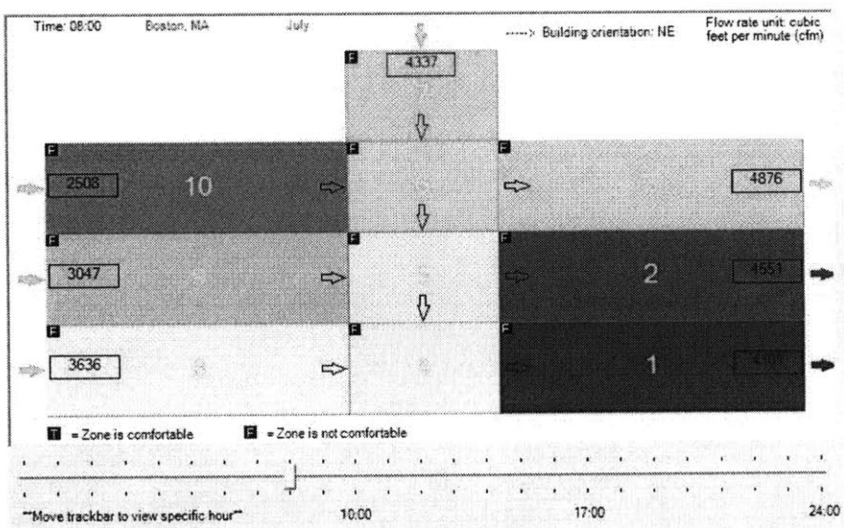


Figure 4.1: Animation Building Drawing. This portion of CoolVent's visualization window provides users a twenty-four hour transient animation building drawing with zone-by-zone color-coded temperature results and air flow rates.

Animation Building Drawing

The first of these attributes, the twenty-four hour transient animation building drawing, provides a twenty-four hour animation of building design results with zone-by-zone color-coded temperature results and air flow rates (Figure 4.1). The first modification to this attribute was the

Attribute	Brief Description	User Interface Issue	Technical / Software Issue
Twenty-Four Hour Transient Animation Building Drawing	Provides a twenty-four hour animation of building design results with zone-by-zone color-coded temperatures, and air flow rates.	• Added labels to the transient animation time bar for times (10:00, 17:00, 24:00) and "**Move Trackbar to View Specific Hour**" Instructions • Updated zone number font so that it always fits in the zone. • Addition of city name and month on animation drawing.	--
Transient Simulation Animation Controls	Allows users to control the animation progression view a text file summary of the temperature and air flow rates for the building design, and individual zone temperature plots versus the ambient temperature.	• Corrected the zone temperature variation plot selection to move instructions outside of the selection box. • Organized all settings into a group.	• Corrected the animate and play/pause buttons
Transient and Steady State Simulation Display Setting Controls	Allows users to control the display settings for the animation display: the air flow visibility, the zone number visibility, the temperature gradient settings and the display interval.	• Organized all settings into a "Display Setting" group.	• Fixed the color selection to re-enable custom color gradient selection and default color gradient restoration.
Transient Simulation Thermal Comfort Modeling Results Access	Allows the user to view a text file summary of the Thermal Comfort Modeling results and the Thermal Comfort Results window (both described in the next section).	• Addition of quick glance comfort models onto the animation screen (T/F) • Organized all settings into "Thermal Comfort Modeling" group.	

Table 4.1: Visualization Window Attributes.

addition of labels to the animation time bar. An instruction label, "**Move the Trackbar to View Specific Hour**," was added near the time bar to help explain the bar's function. Additionally, a few time labels (10:00, 17:00 and 24:00) were added to the bar. Beyond modification to the time bar, the city name and month for the simulation were added to the animation drawing to prevent architects from having to go back to the base interface window to remember their selections. Also, the zone number font was updated so that it always fits in the corresponding building drawing box.

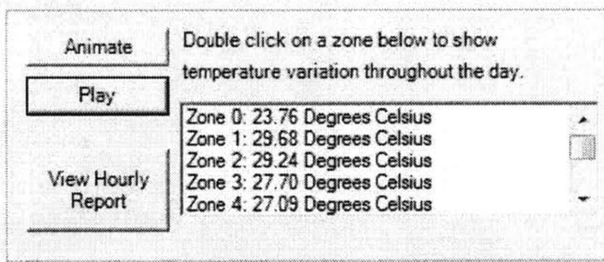


Figure 4.2: Transient Simulation Animation Controls. These controls allow architects to control the animation of their building design's results , to view an hourly text file report of their simulation, and to view hourly plots of zone comfort.

Animation Controls

The controls for the transient simulation animation were also modified (Figure 4.2). The transient simulation animation "Animate" and "Pause/Play" buttons control the flow of the animation. The buttons have been corrected to appropriately show pause if an animation has been restarted or if an animation has been paused, or play otherwise. The transient simulation animation controls also include a button for accessing a text file summary of transient simulation temperature and airflow results as well as a button for viewing individual plots of zone temperatures versus the ambient temperature. Previously, the zone temperature variation plot selection instructions were located inside the selection box, causing the program to crash every time the instructions were double-clicked. The instructions have been moved outside of the selection box to protect program stability. Additionally, the "Animate" button, the "Pause/Play" button, the text summary button and the zone temperature variation plot selection have been combined into a boxed group on the Visualization window to add clarity to the interface that these features are all incorporated with animation controls.

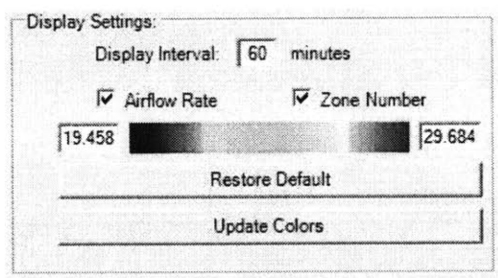


Figure 4.3: Display Settings. Architects can control the color gradient of the animation panel.

Display Setting Controls

The transient and steady state simulation display setting controls allow architects to control settings for the animation drawing: the air flow visibility, the zone number visibility, temperature gradient limits and animation time interval (Figure 4.3). This attribute was modified in two ways. In terms of the user interface, the display controls were all organized into a "Display Settings" box. Additionally, the color selection was updated to enable custom color gradient selection and default color gradient restoration in the animation drawing (Figure 4.4).

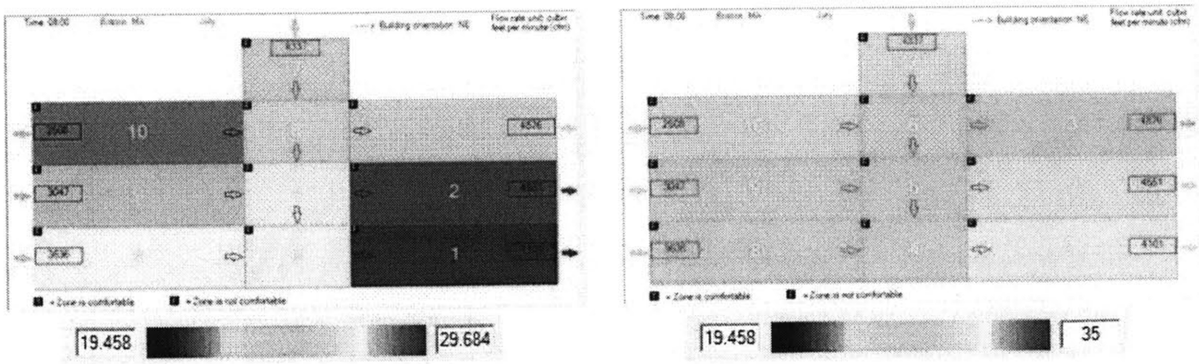


Figure 4.4: Custom Color Gradient Selection. Using the display settings window, architects can control the coloration of the animation panel to any gradient range. They can also restore the color range to default gradient settings.

Thermal Comfort Modeling Results Access

The final visualization attribute – the transient simulation thermal comfort modeling results access (Figure 4.5) – allows the architects to view a text file summary of the Thermal Comfort Modeling results and the Thermal Comfort Results window (both as discussed in Section 5).

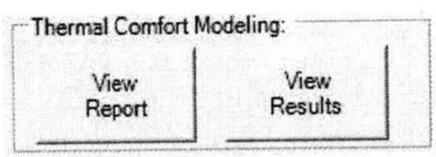


Figure 4.5: Thermal Comfort Modeling Results Access. The "View Report" button allows architects to view a text file summary of the later discussed thermal comfort modeling. The "View Results" button allows architects to view the thermal comfort modeling results window.

These controls were added to the visualization to enable access to the developed thermal comfort modeling for CoolVent and were grouped into the "Thermal Comfort Modeling" box to ensure that architects knew that the "View Report" and "View Results" buttons were associated with thermal comfort modeling. Further, quick glance access to thermal comfort model results was added to the animation screen (Figure 4.6). This addition allows users to gain a full understanding of temperature, air flow and whether or not a zone is comfortable from the animation drawing without having to view the full thermal comfort modeling results window.

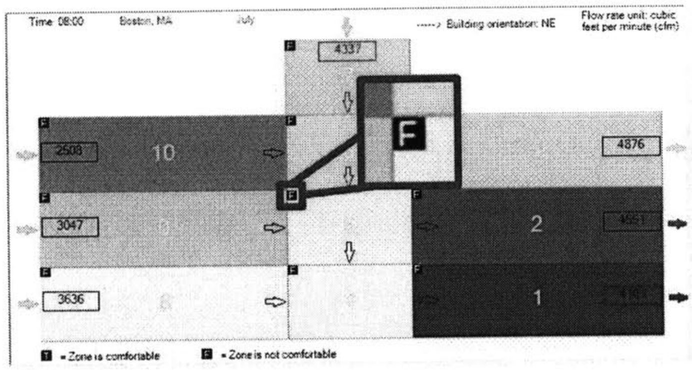


Figure 4.6: Quick Glance Access to Thermal Comfort Results. True (T) and False (F) icons were added to the animation drawing to allow users to quickly understand comfort in their building's design at a given time.

5 Thermal Comfort Modeling & Results

After improving CoolVent's base interface and visualization window, CoolVent's results were expanded to allow architects to understand how their design choices not only effect the temperature and airflow in each of the zones of their building design but also how their design choices effect the overall comfort throughout the zones of their building. There were four stages in the development of these results– an understanding of comfort standards and the development of a thermal comfort model, the development of a thermal comfort input tab for CoolVent's base interface, the development of the thermal comfort model initial results and the development of more complex thermal comfort model results through a thermal comfort results window.

5.1 Thermal Comfort Model

The standards for thermal comfort in building design are described by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in the 2009 ASHRAE Handbook – Fundamentals (SI Edition) and follow the guidelines of ASHRAE *Standard* 55 [1]. A summary of these standards, as defined by temperature, humidity ratio and relative humidity are plotted by ASHRAE on a psychrometric chart for both summer and winter (Figure 5.1.1).

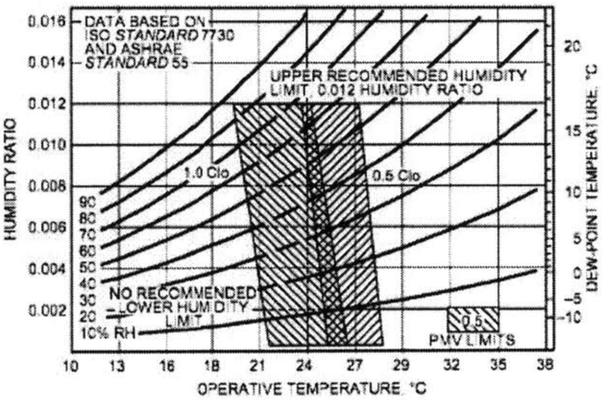


Figure 5.1.1: ASHRAE Thermal Comfort Standards

The psychrometric chart presents two shaded regions of comfort – one region representing 1.0 clo (a full business suit or clothing levels expected during winter months) and the other region representing 0.5 clo (a short-sleeved shirt and trousers or clothing levels expected during summer months). Each shaded region is limited by an approximate upper humidity ratio of 0.012, a boundary where discomfort due to moisture surpasses acceptable limits. ASHRAE standards note that low humidity and consequently dry nose, throat, eyes and skin can cause discomfort; however, there is no lower limit defined by ASHRAE for comfortable humidity ratio. Consequently, from these psychrometric charts, there is a clear, linear relationship between humidity ratio and the minimum and maximum temperature boundaries for comfort on an approximate range of humidity ratios, 0 – 0.012. It is this linear relationship that lends to a straight-forward model for thermal comfort and an obtainable addition to the CoolVent tool.

In developing a model for determining thermal comfort within the CoolVent results, two key data were available – the relative humidity per hour from the weather data files and the temperature results (as presented in the building animation) by zone per hour (Figure 5.1.2). By manipulating this data and determining the minimum and maximum temperature thresholds for each zone per hour, an effective thermal comfort model was developed in parallel to CoolVent's current building animation for 0.5clo. The model was centered at 0.5clo to allow for attention to the transitional months between spring and summer and the months between summer and fall when buildings are trying to avoid the use of air conditioning and mechanical cooling in the United States. It was assumed that there were no moisture sources internal to the building.

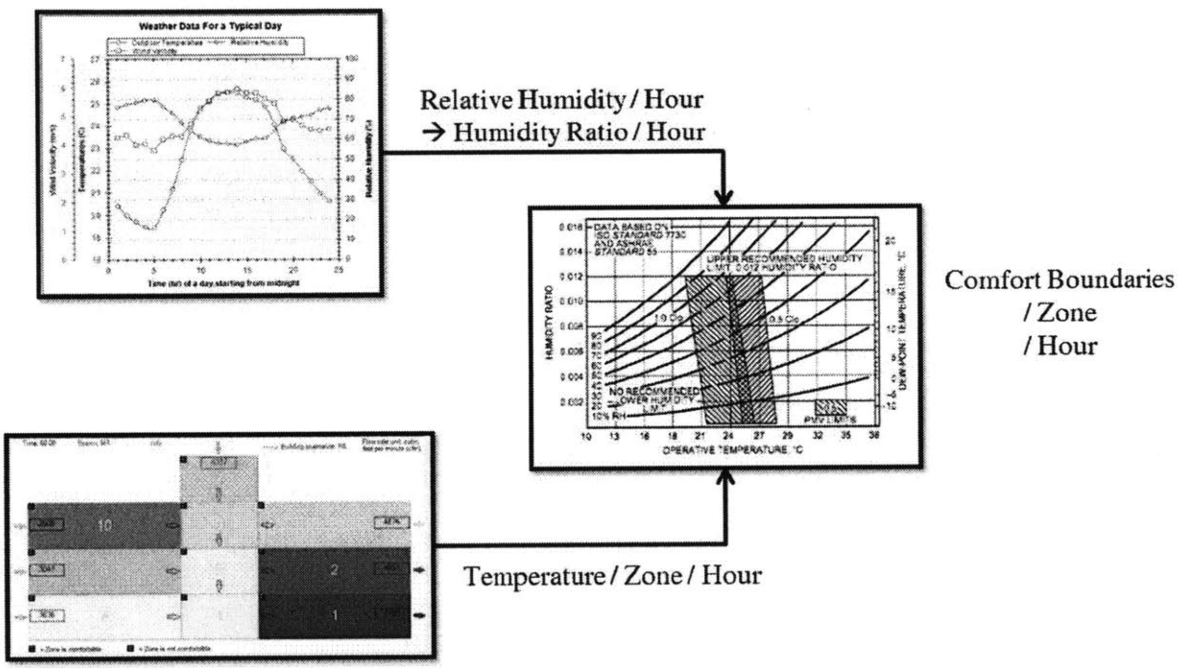


Figure 5.1.2: CoolVent Thermal Comfort Model.

Additionally, CoolVent's thermal comfort modeling was also designed to have the option for a custom thermal comfort model. This model would allow *users* to define a universal minimum and maximum humidity ratio and minimum and maximum temperature threshold for comfort. They could then select this model or the ASHRAE model in the base interface to have added flexibility when determining comfort for their building design. With two thermal comfort modeling schemes designed (Figure 5.1.3), CoolVent's base interface was modified to support these models.

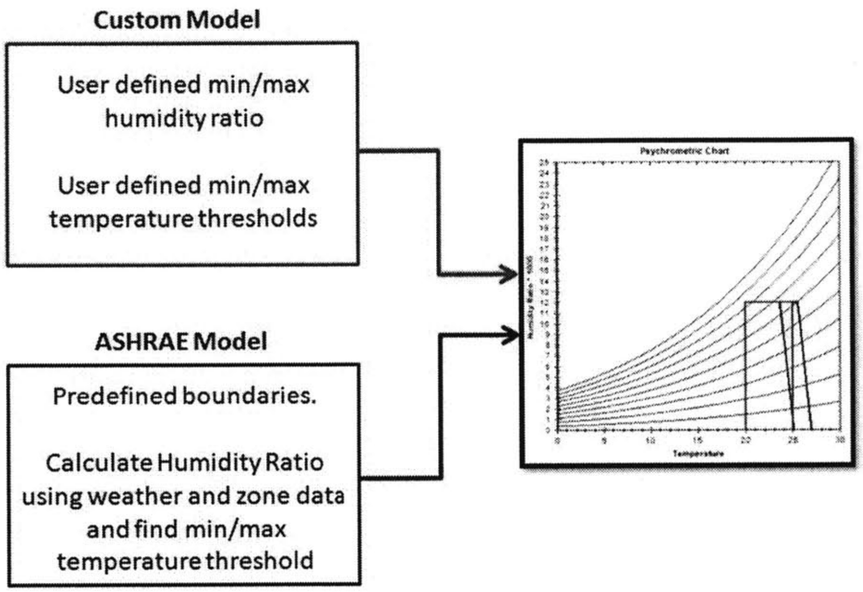


Figure 5.1.3: Two CoolVent Thermal Comfort Models.

5.2 Thermal Comfort Tab Page

With two comfort models supported within the CoolVent system, the base interface was modified by adding a new *Thermal Comfort Models* tab. The design of this tab had three major goals: allowing users to select the comfort model they wanted to use to analyze their building, allowing users to input temperature and humidity ratio boundaries if applicable and providing some feedback to the user on their selected comfort model.

The first of these goals was accomplished similarly to the selection of a transient or steady state simulation on the Main Inputs tab of the base interface. A Comfort Model Selection bar was added to the Thermal Comfort Models tab to allow users to select the appropriate model – *Custom Thermal Comfort Model* or *2009 ASHRAE Handbook Thermal Comfort Model* (Figure 5.2.1).

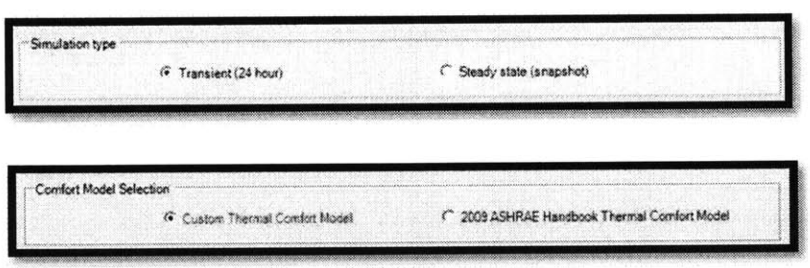


Figure 5.2.1: Thermal Comfort Model Selection. Architects can choose between a custom thermal comfort model and ASHRAE standards.

If the custom comfort model is selected, four inputs are needed: the minimum allowable humidity ratio, the maximum allowable ratio, the minimum allowable temperature and the maximum allowable temperature. Alternatively, if the ASHRAE model is selected, no additional inputs are needed from the user, as all humidity ratio and temperature boundaries for 0.5clo are specifically defined by ASHRAE. This need for inputs only for the comfort model suggested that I needed a box of four text inputs that would only be visible when the custom model was selected from the comfort model selection box (Figure 5.2.2).

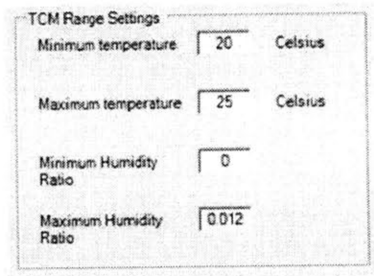


Figure 5.2.2: Custom Comfort Model Input Box. For the custom thermal comfort model, architects define minimum and maximum allowable temperatures and humidity ratios.

Finally, the user needed feedback on their selected comfort model. Given AHSRAE's presentation of their thermal comfort standards on a psychrometric chart, it was only appropriate that users could get feedback on their selected comfort model on a similar psychrometric chart. By having two containing boxes on a psychrometric chart, one blue box representing ASHRAE standards and one red box representing custom standards, users can clearly see their custom defined thresholds and can additionally compare their custom model to ASHRAE standards. For the custom model, the software defaults placed comfort within humidity ratios of 0-0.012 and temperatures of 0-25°C. As these values were changed, a red box representing the custom model settings would move in response on a neighboring psychrometric chart. For example, if the maximum temperature threshold for comfort were increased to 28°C, the red containing box would expand to the right.

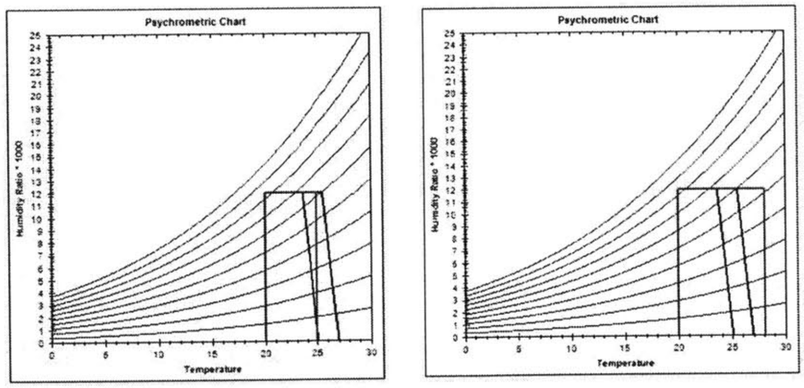


Figure 5.2.3: Comfort Boundaries on Psychrometric Charts. The psychrometric chart on the base interface Thermal Comfort Modeling Tab allows users to see their custom comfort boundary selections (red) versus the ASHRAE defined standard boundaries (blue).

For the ASHRAE model, the red containing box, representing custom model settings, would no longer be visible. This thermal comfort model selection, custom model input box, and psychrometric chart combined into the final version of the Thermal Comfort Models tab on CoolVent's base interface (Figure 5.2.4).

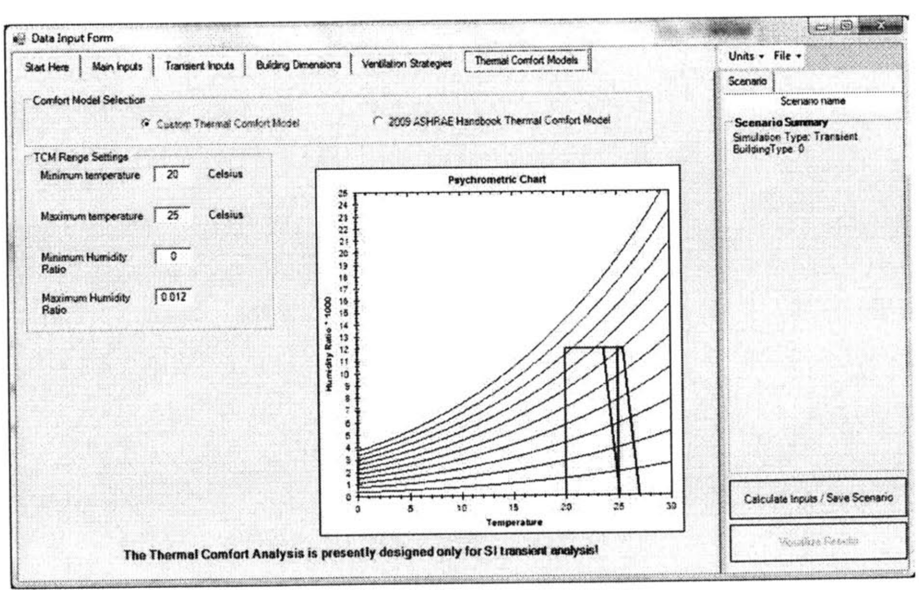


Figure 5.2.4: CoolVent's Thermal Comfort Model Tab.

5.3 Thermal Comfort Initial Results

With a thermal comfort model and input tab on CoolVent's base interface, basic thermal comfort model results were developed. Using the existing animation drawing on CoolVent's Visualization Window, true-false indicators were added to each zone box's upper left-hand corner for each hour of the day (Figure 5.3.1). If a zone was comfortable for a given hour the box would read "T," otherwise the box would read "F." This provided users with a quick glance understanding of not only the temperature and air flow rates for the zones in their building design but also of the comfort of those zones.

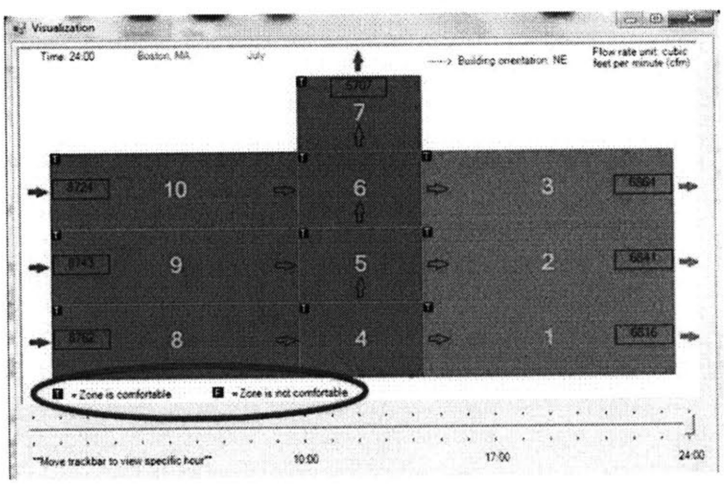


Figure 5.3.1: True/False Zone Comfort. True (T) and False (F) indicators were added to the animation drawing to allow for a quick glance understanding of a building's comfort.

Additionally, a text file report was developed for thermal comfort results. This file provided more information than simply whether a zone was comfortable or not; it provided a summary by hour of all the zones' temperatures, humidity ratios, minimum temperature thresholds for comfort, maximum temperature thresholds for comfort, minimum humidity ratio threshold for comfort, maximum humidity ratio thresholds for comfort and comfort. The first hour's result for a custom thermal comfort model analysis is shown in Figure 5.3.2. The custom model specifies comfortable zones as zones with temperatures from 17-25°C and humidity ratios from 0-0.012 (the same standard for humidity ratio as ASHRAE). For the first hour, zones 1-3 are all comfortable while the remaining zones are uncomfortable because they are too cold.

This simulation is transient.
The simulated city is: Boston, MA.
Weather Data File: USA_MA_Boston-Logan_TMY2.epw
The simulated month is: June.
The building orientation is: 50 Degrees.

Temperatures are reported in Degrees Celsius.
Airflows are reported in kg/s.

Hour 1

Zone	Temperature	HR	MinTemp	MaxTemp	minHR	maxHR	Comfortable?
0	16.5882	0.0090	17	25	0	0.012	False
1	17.2517	0.0094	17	25	0	0.012	True
2	17.2505	0.0094	17	25	0	0.012	True
3	17.2494	0.0094	17	25	0	0.012	True
4	16.8829	0.0092	17	25	0	0.012	False
5	16.8836	0.0092	17	25	0	0.012	False
6	16.8844	0.0092	17	25	0	0.012	False
7	16.8938	0.0092	17	25	0	0.012	False
8	16.8767	0.0092	17	25	0	0.012	False
9	16.8777	0.0092	17	25	0	0.012	False
10	16.8786	0.0092	17	25	0	0.012	False

Figure 5.3.2: Text File Summary of Comfort.

While this text file summary provided more information about zone comfort, i.e. whether a zone was too hot or too humid for the selected comfort model, more results were needed within CoolVent's interface to allow users to intuitively understand their building designs' comfort and how they could improve their designs.

5.4 Thermal Comfort Results Window

CoolVent's Thermal Comfort Results Window was designed to provide extensive insight into a building design's comfort given a selected comfort model using the following breakdown of comfort:

- Comfortable
- High Temperature Only
- Low Temperature Only
- High Humidity Only
- High Humidity & High Temperature
- High Humidity & Low Temperature
- Low Humidity Only
- Low Humidity & High Temperature
- Low Humidity & Low Temperature

The comfort results feature four results sections: a full building summary with temperature-based pie charts, temperature plots for all building zones zone during an average day, psychrometric chart summaries of comfort for each zone and color-bar representations of comfort for each zone. The header for the window provides users with a quick glance reference of their selected comfort model as well as of the city and month in which they are analyzing their building design (Figure 5.4.1).

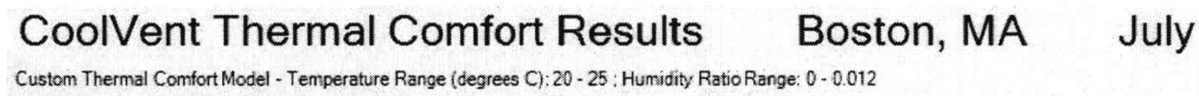


Figure 5.4.1: CoolVent Thermal Comfort Results Window Header.

Full Building Summary (Pie Charts)

The first results section – the full building summary of temperature-based comfort using pie charts – provides a summary of temperature-based building comfort by zone. Consider zone 1 in Figure 5.4.2. This zone's pie chart (and corresponding percentage text to the right of the zone number) explains that the zone is too hot for the defined comfort metric 50% of the time. The zone is also uncomfortable for an additional 12% of the day, a time when it is too cold. The zone is, however, comfortable (when not considering humidity concerns) for 38% of the day. Zone 10, on the other hand, is comfortable for 55% of the day, the remainder of which it is too hot.

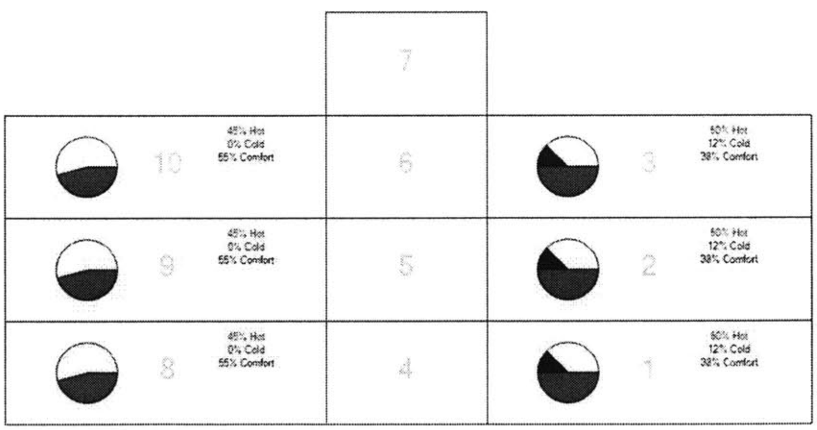


Figure 5.4.2: Full Building Summary (Pie Charts). The pie charts reflect the percentage of the day that a given zone is too hot, too cold or comfortable based on the selected comfort metric. It is possible that a zone marked comfortable on the pie charts is too humid.

This full building view of comfort, based on temperature, provides a great tool for architects to begin to spatially understand comfort in their building designs. They can easily see that zones on one side of the building (zones 8-10) are more comfortable than those on the other side of the building (1-3). They can also easily see that no zone has achieved 100% comfort for the day. They can then begin to make modifications to their building design or building orientation, accordingly.

Temperature Plots by Zone

The second results section – the temperature plots by zone – also allows architects to gain an understanding of full building comfort at a glance (Figure 5.4.3).

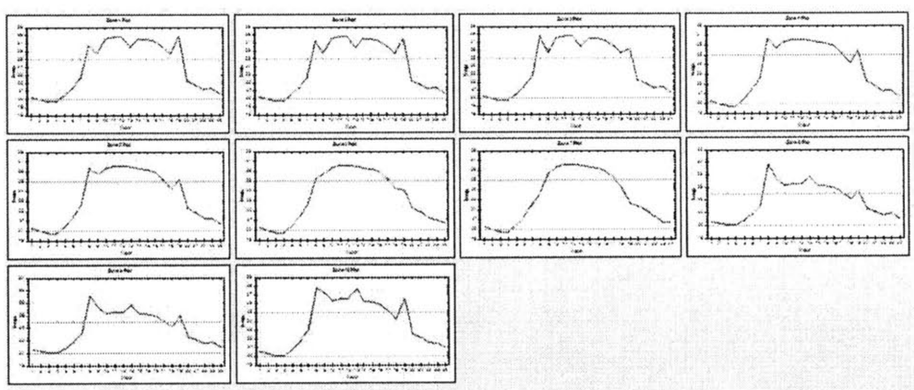


Figure 5.4.3: Temperature Plots by Zone.

Unlike the pie charts, these plots can tell an architect how far from comfortable a zone is. Also, these plots are not spatially arranged as the pie charts were within the building diagram. (This spatial information can be accessed from a building layout reference diagram (Figure 5.4.4), however.)

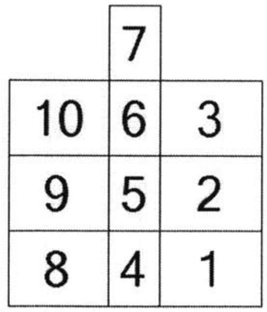


Figure 5.4.4: Building Layout Reference Diagram.

While these plots together provide a full building understanding of zone comfort, the zoom button to the right of these plots allows architects to zoom and scroll to a zone of interest. For example, consider the plot of temperatures for zone 1 (Figure 5.4.5).

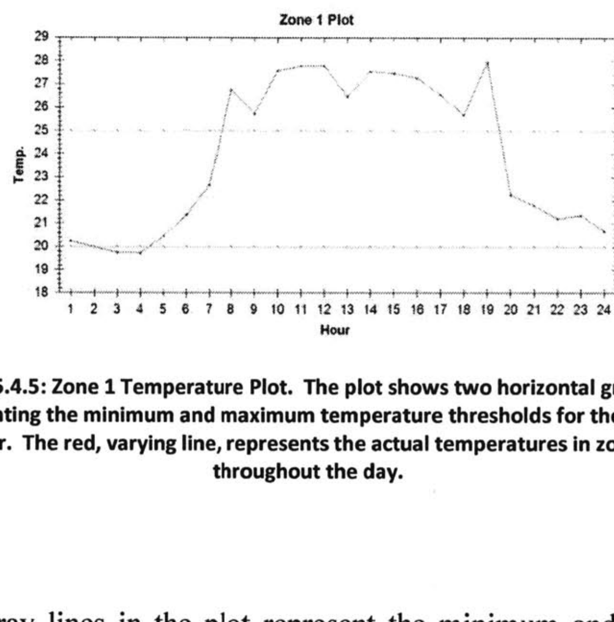


Figure 5.4.5: Zone 1 Temperature Plot. The plot shows two horizontal gray lines representing the minimum and maximum temperature thresholds for the zone by hour. The red, varying line, represents the actual temperatures in zone 1 throughout the day.

The two, horizontal gray lines in the plot represent the minimum and maximum temperature thresholds for the zone by hour. (For ASHRAE comfort models these thresholds vary with the humidity ratio at each hour.) The red line in the plot represents the actual temperatures in zone 1 by hour (as calculated by CoolVent). From the pie chart results, an architect could learn that zone 1 was too hot for 50% of the day; however, by viewing this temperature plot, the architect can additionally learn that zone 1 was too hot from hour 8 until hour 19. An architect can also know from this plot that zone 1 was hottest at the 19th hour of the day. On the other side of comfort, the architect could also learn that the 12% of the day that the zone was too cold was from hour 3 to hour 4. If the architect was designing a commercial space, he might decide that discomfort at those times did not affect the validity of his design. The architect could still, however, learn nothing definite about possible humidity concerns from these temperature plots.

Psychrometric Chart Summary by Zone

The next results section – the psychrometric chart summary by zone – is the first results page where architects can gain a full understanding – temperature and humidity based – of zone comfort throughout the day. These psychrometric charts provide direct reference back to the psychrometric charts from the Thermal Comfort Models tab on CoolVent's base interface – the red box representing custom thermal model specifications (if selected) and the blue box representing ASHRAE standards for comfort.

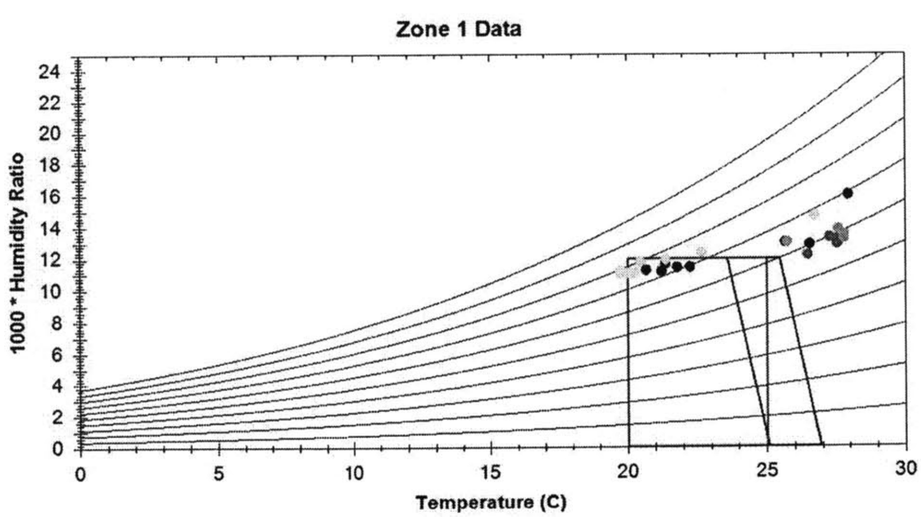


Figure 5.4.6: Psychrometric Chart for Zone 1.

From the psychrometric chart for zone 1 (Figure 5.4.6), an architect can observe the hourly progression of temperature -and humidity (lighter colors representing earlier hours and darker colors representing later hours). He can also see that times during the middle of the day (mid-blue colors) are too hot and have too high of a humidity ratio to be comfortable. If an architect is using a custom model, he can easily determine from these plots if the zone would be acceptable under ASHRAE standards, instead of his custom standards, without having to run a new simulation.

Colorbar Representation by Zone

The final thermal comfort model results section – the color bar representations of comfort by zone – allows architects another full understanding (temperature and humidity) of comfort for their building design (Figure 5.4.7).

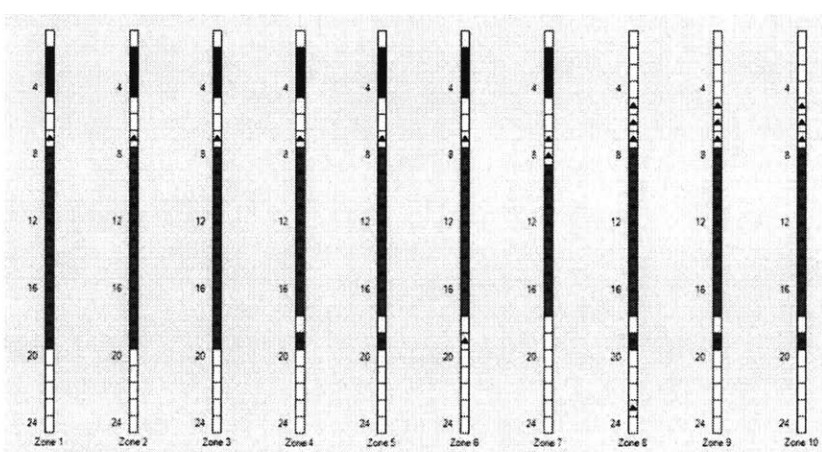


Figure 5.4.7: Colorbar Representation by Zone.

Unlike with the psychrometric charts by zone, this result allows for an understanding of all of the zones side-by-side. As with the temperature plots, it does not preserve the spatial relationship between the zones; however, as before a building diagram is on the tab for reference. For these plots, overheating is represented by red shaded hours, hours that are too cold are represented by blue shading and humidity concerns are represented by upwards and downwards pointing arrows, for high and low humidity ratios respectively. A zone that is comfortable (both in temperature and humidity) will be white with no arrow for a given hour.

5.5 Adaptive Thermal Comfort Standard

To complement the ASHRAE-based thermal comfort modeling, an adaptive thermal comfort standard was added to CoolVent's temperature plots by zone. In addition to showing the actual temperature as well as the minimum and maximum temperature thresholds for the zone, the temperature plots now additionally feature two green lines (Figure 6.1.2).

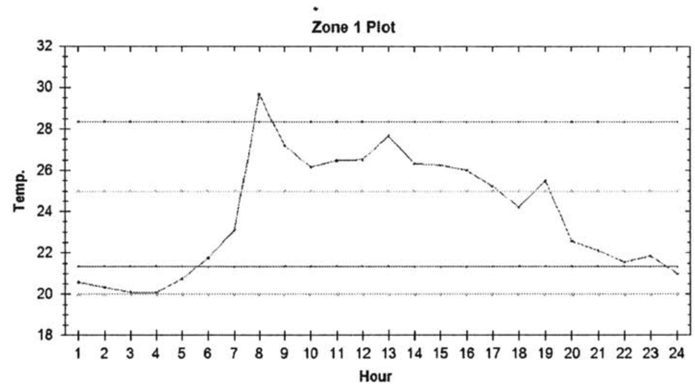


Figure 5.5.1: Modified Temperature Plots by Zone. Green lines have been added to the zone temperature plots to represent minimum and maximum temperature thresholds based on adaptive thermal comfort standards developed by Brager and Dear.

The green lines represent the minimum and maximum temperature thresholds based on an adaptive thermal comfort standard. Adaptive comfort, as described by Brager and Dear [2], takes into account the complex ways in which people interact with their environments and focuses on three modes of adaptation: physiological, behavioral and psychological. Through analyzing 21,000 data sets over 160 office buildings, Brager developed an adaptive comfort metric based on mean monthly outdoor temperatures (Figure 6.1.3).

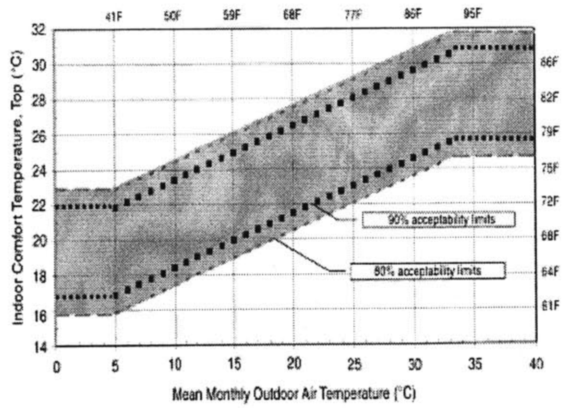
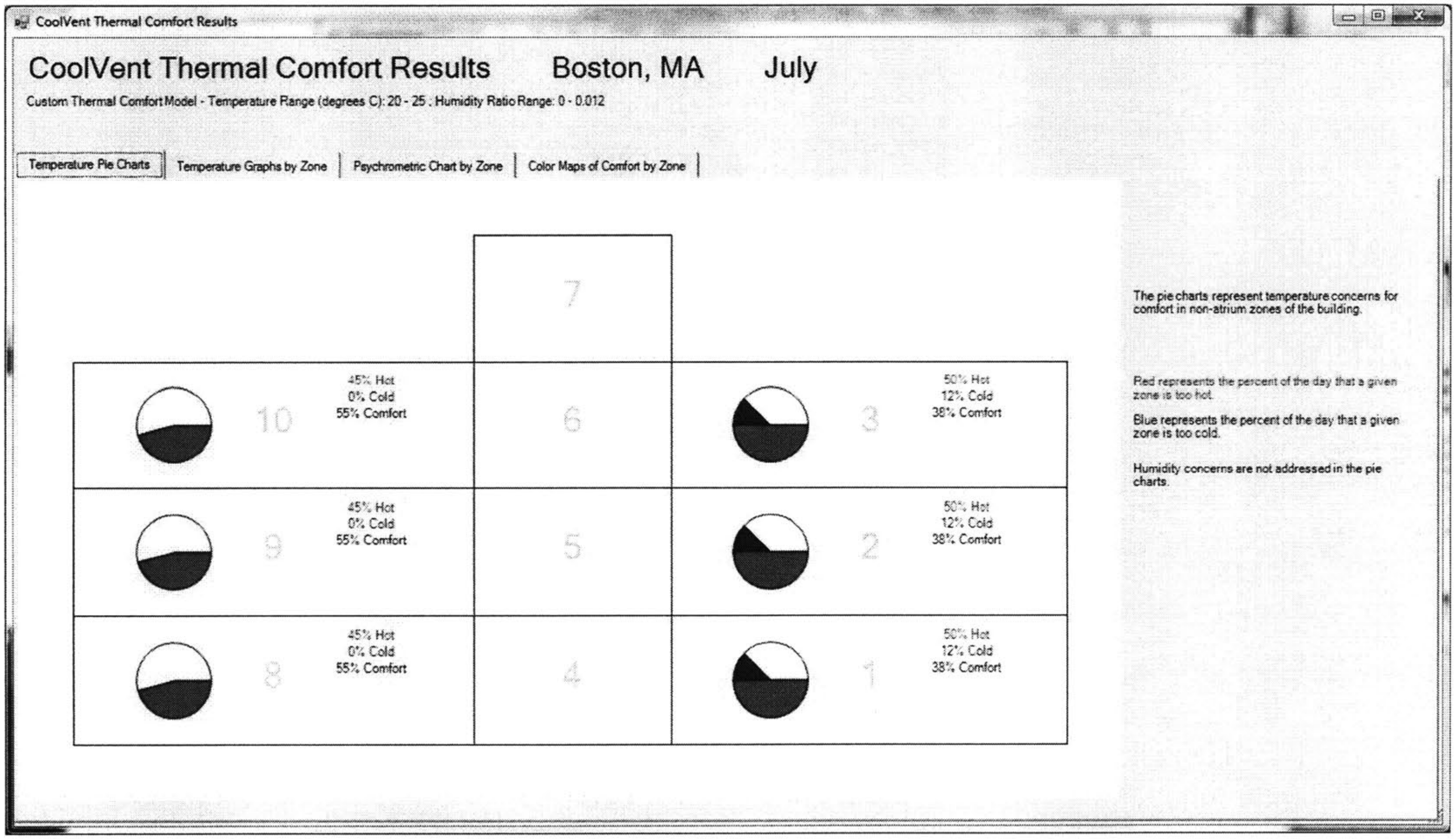
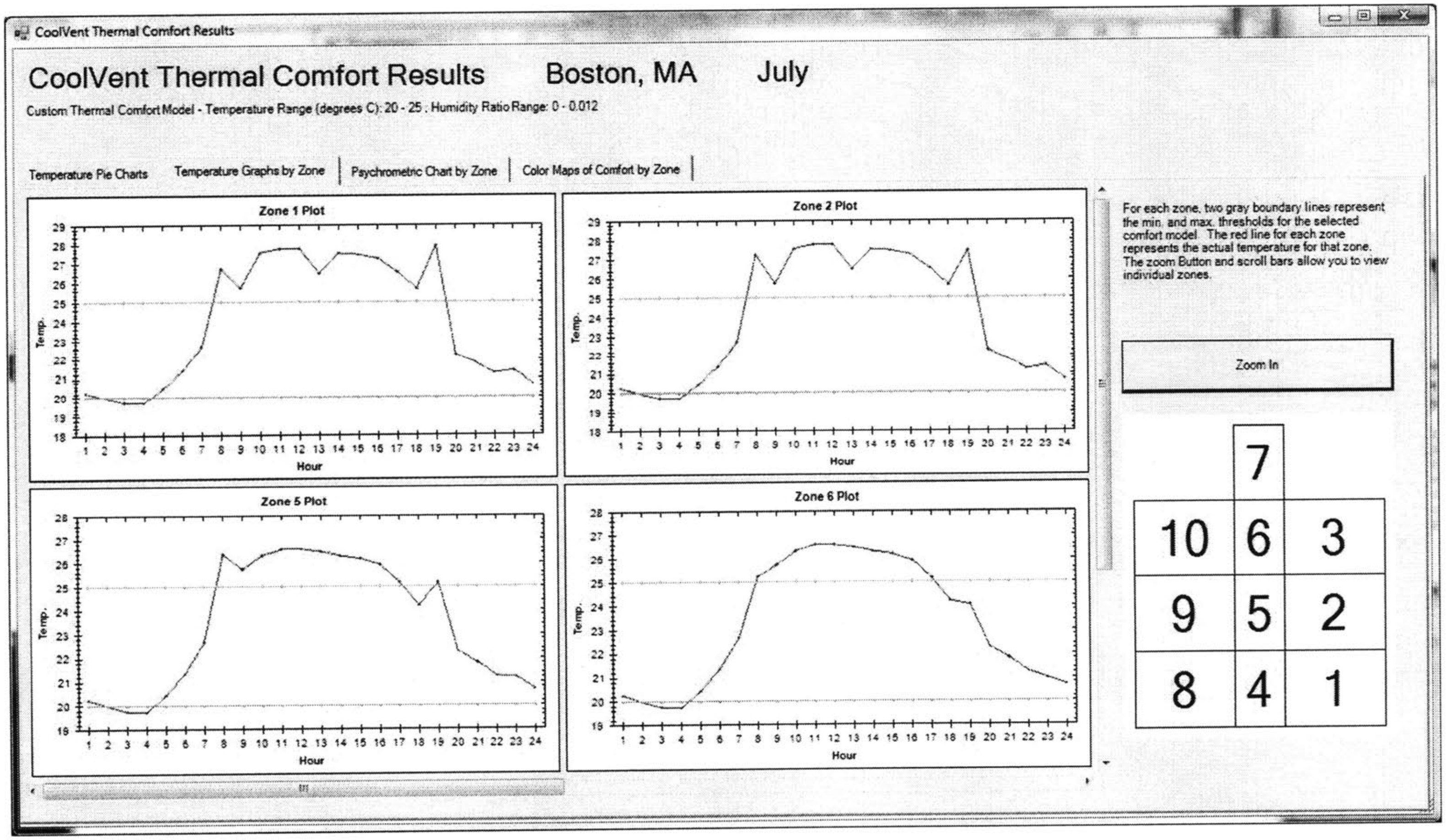
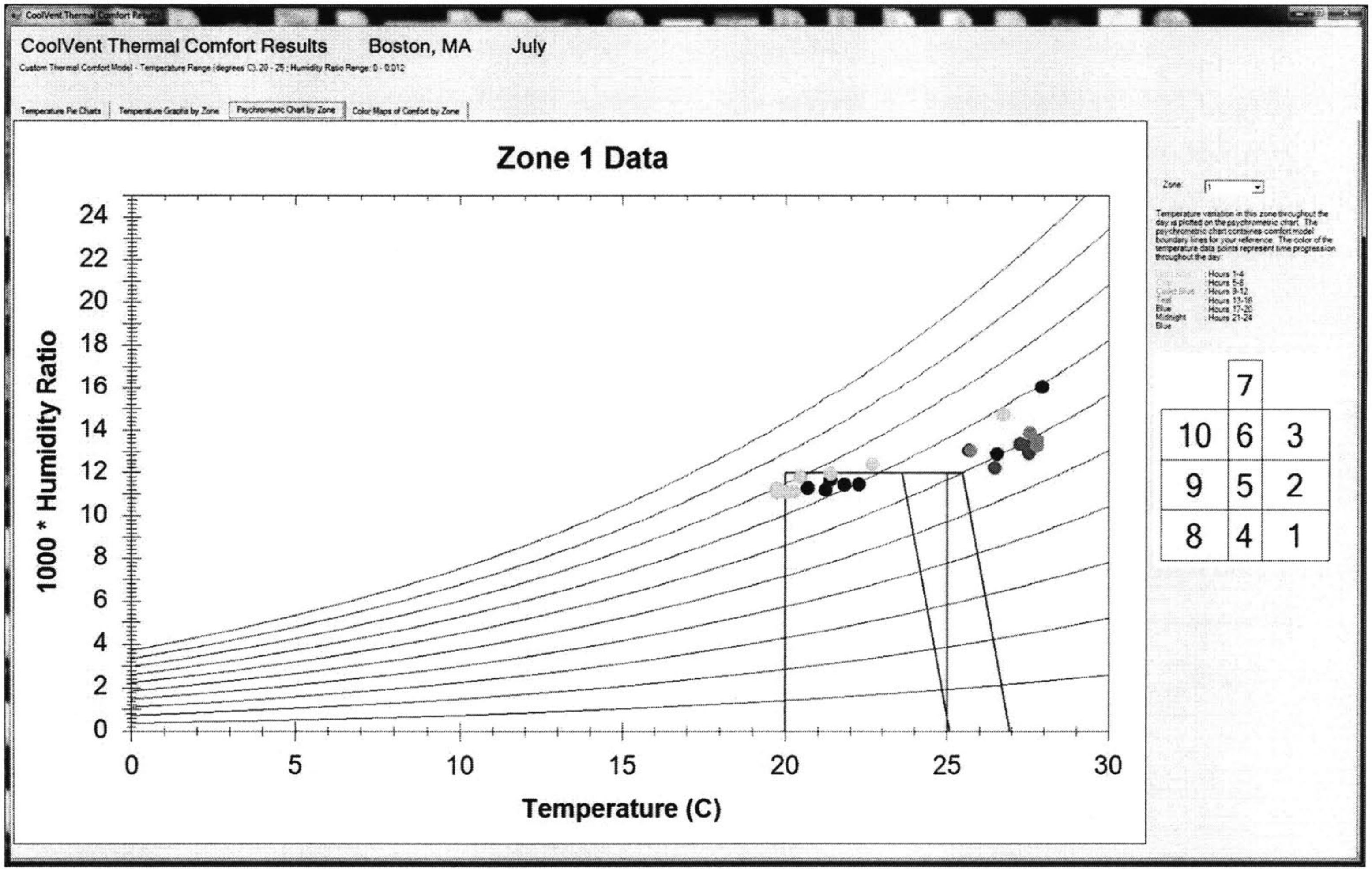


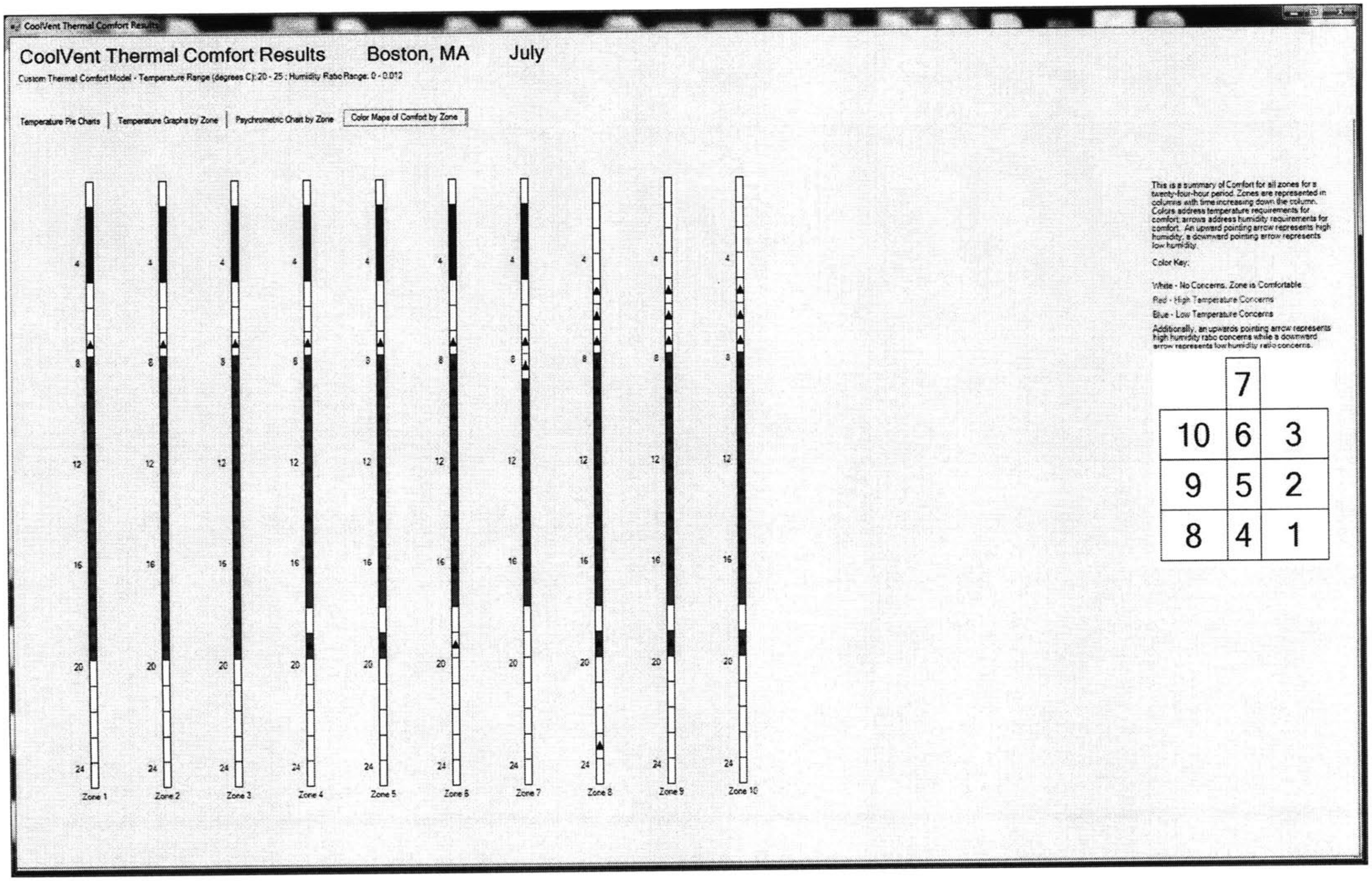
Figure 5.5.2: Brager and Dear's Adaptive Comfort Standard.

This metric was added to CoolVent to allow architects to understand their buildings' comfort beyond the laboratory defined ASHRAE standards, to understand building occupants' abilities to adapt to thermal conditions in naturally ventilated buildings.


CoolVent Thermal Comfort Results
CoolVent Thermal Comfort Results
Boston, MA
July
Custom Thermal Comfort Model - Temperature Range (degrees C): 20 - 25 ; Humidity Ratio Range: 0 - 0.012
Temperature Pie Charts
Temperature Graphs by Zone
Psychrometric Chart by Zone
Color Maps of Comfort by Zone
7
10
45% Hot
0% Cold
55% Comfort
6
3
50% Hot
12% Cold
38% Comfort
9
45% Hot
0% Cold
55% Comfort
5
2
50% Hot
12% Cold
38% Comfort
8
45% Hot
0% Cold
55% Comfort
4
1
50% Hot
12% Cold
38% Comfort
The pie charts represent temperature concerns for comfort in non-atrium zones of the building.
Red represents the percent of the day that a given zone is too hot.
Blue represents the percent of the day that a given zone is too cold.
Humidity concerns are not addressed in the pie charts.


CoolVent Thermal Comfort Results
CoolVent Thermal Comfort Results
Boston, MA
July
Custom Thermal Comfort Model - Temperature Range (degrees C): 20 - 25 ; Humidity Ratio Range: 0 - 0.012
Temperature Pie Charts
Temperature Graphs by Zone
Psychrometric Chart by Zone
Color Maps of Comfort by Zone
Zone 1 Plot
Zone 2 Plot
Zone 5 Plot
Zone 6 Plot
Temp.
Hour
For each zone, two gray boundary lines represent the min. and max. thresholds for the selected comfort model. The red line for each zone represents the actual temperature for that zone. The zoom Button and scroll bars allow you to view individual zones.
Zoom In
7
10
6
3
9
5
2
8
4
1


CoolVent Thermal Comfort Results
CoolVent Thermal Comfort Results Boston, MA July
Custom Thermal Comfort Model - Temperature Range (degrees C): 20 - 25 ; Humidity Ratio Range: 0 - 0.012
Temperature Pie Charts
Temperature Graphs by Zone
Psychrometric Chart by Zone
Color Maps of Comfort by Zone
Zone 1 Data
1000 * Humidity Ratio
0
2
4
6
8
10
12
14
16
18
20
22
24
0
5
10
15
20
25
30
Temperature (C)
Zone: 1
Temperature variation in this zone throughout the day is plotted on the psychrometric chart. The psychrometric chart containes comfort model boundary lines for your reference. The color of the temperature data points represent time progression throughout the day:
: Hours 1-4
: Hours 5-8
: Hours 9-12
Teal : Hours 13-16
Blue : Hours 17-20
Midnight Blue : Hours 21-24
7
10
6
3
9
5
2
8
4
1


CoolVent Thermal Comfort Results
CoolVent Thermal Comfort Results
Boston, MA
July
Custom Thermal Comfort Model - Temperature Range (degrees C): 20 - 25 ; Humidity Ratio Range: 0 - 0.012
Temperature Pie Charts
Temperature Graphs by Zone
Psychrometric Chart by Zone
Color Maps of Comfort by Zone
4
8
12
16
20
24
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
Zone 6
Zone 7
Zone 8
Zone 9
Zone 10
This is a summary of Comfort for all zones for a twenty-four-hour period. Zones are represented in columns with time increasing down the column. Colors address temperature requirements for comfort; arrows address humidity requirements for comfort. An upward pointing arrow represents high humidity; a downward pointing arrow represents low humidity.
Color Key:
White - No Concerns, Zone is Comfortable
Red - High Temperature Concerns
Blue - Low Temperature Concerns
Additionally, an upwards pointing arrow represents high humidity ratio concerns while a downward arrow represents low humidity ratio concerns.
7
10
6
3
9
5
2
8
4
1

6 User Study

Throughout CoolVent's development, interaction with CoolVent's users has been quintessential in its improvement. The three aspects of this interaction were: general feedback during CoolVent's development, the CoolVent game with Harvard's Graduate School of Design (GSD) and an MIT web-based user study. The major results from these interactions are discussed in this chapter.

6.1 General Feedback in Developing CoolVent

Professor Leon Glicksman, Alejandra Menchaca-B., Diego Ibarra, and many other architects and engineers have provided significant feedback throughout CoolVent's development. Beyond the modifications discussed in previous chapters, their suggestions have led to one change: a modification of the presentation of comfort results in the visualization animation window.

Visualization

The presentation of comfort results in the visualization animation window was modified so that instead of the comfort results being represented by true (T) or false (F), they are represented by comfortable (C) or uncomfortable (U). This modification allows for the architects to more intuitively understand what the boxes in the animation drawing represent – comfort. The labels below the building drawing in the animation window were modified to reflect this change (Figure 6.1.1).

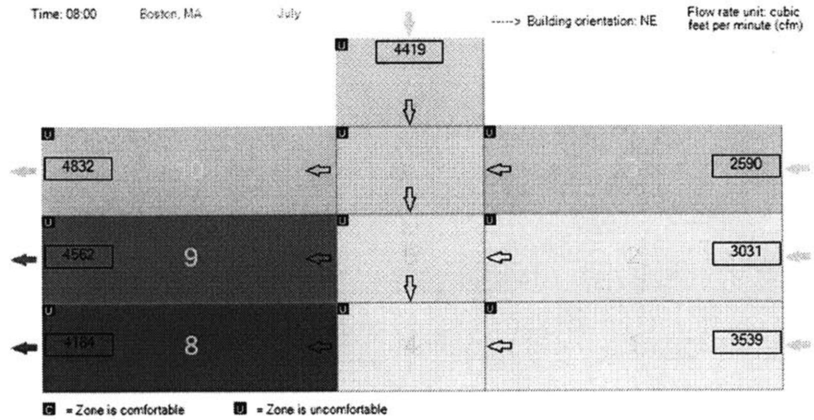


Figure 6.1.1: Modified Visualization Animation Window. The window now reflects comfort using a comfortable (C) or uncomfortable (U) metric, instead of the previous true (T) or false (F) metric.

6.2 Harvard GSD CoolVent Game

In addition to general feedback throughout CoolVent's development, significant feedback was gained from a version of CoolVent developed for a building design game at Harvard's Graduate School of Design (GSD) with Professor Christoph Reinhart and Diego Ibarra. The goal of the game was to "design a naturally ventilated office building in Boston with a minimum amount of overheating using CoolVent." The game relied on a Thermal Overheating Index (TOI) defined as an area weighted percentage of occupied hours per day for which a building is overheated. The complete rules and procedures for the game are outline in Appendix A of this report.

From the game, it became clear that the installation process for the CoolVent software was insufficient. There was a lot of confusion regarding the installation of Java Runtime which is needed to run the CoolVent's calculations. Without Java, students at the design school were running the software only to see the base case of the software running without error, as the data for the base case is saved in the release text files that communicate between the C# and Java components of the tool. To improve this, further attention needs to be paid to installation and clearing the base case from the text files to prevent false positive simulation runs.

Additionally, it became clear that the building dimension inputs and naming conventions, as well as the window calculation tools, were insufficient. These insufficiencies were further investigated in the MIT web-based user study.

6.3 MIT Web-Based User Study

To gain more detailed feedback on CoolVent's interface and CoolVent as an overall tool, a web-based, Google Forms user study was performed (Appendix B). The user study focused on gaining feedback from students currently enrolled at MIT in courses focusing on building design and natural ventilation techniques through four points of questioning: experience with building design and natural ventilation, overall interface experience, specific component usefulness and understanding CoolVent's results. All courses taught CoolVent as a part of their semester's curriculum. Nineteen students were surveyed of which eighteen were graduate students enrolled in environmental health, architecture or building design programs. Students had a variety of backgrounds in areas including architecture, fine arts, mechanical engineering and civil engineering. All study questions were optional.

Of the user study participants, 53% considered themselves novices in building design and natural ventilation while 42% of them considered themselves intermediate users of building design simulation tools, listing experience with: Design Advisor, Ecotect, MultiFrame Structural, LightSolve, DIVA, Radiance for Rhino and Autocad (Figure 6.3.1).

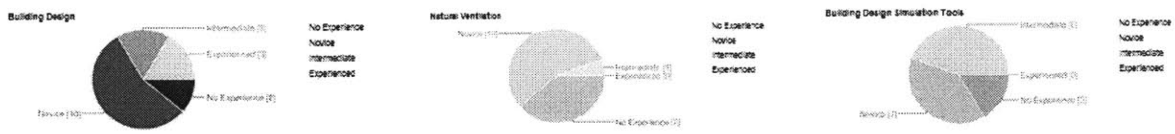


Figure 6.3.1: MIT web-based user study subject backgrounds.

A majority of students found CoolVent a useful tool for building design (58%), a useful tool for determining comfort for building designs (73%), would recommend CoolVent to peers and friends as a general building design tool (53%), would recommend CoolVent to peers and friends as a tool for determining comfort in a building design (64%) and would use CoolVent to help justify a building design to an architectural firm / engineer (52%). However, among this success several areas for improvement surfaced.

Building Dimensioning

CoolVent's building dimensioning was repeatedly criticized. Naming conventions, input errors (at the time there was no input error prevention built into the software) and building drawings were identified as areas that needed to be improved for CoolVent to become intuitive to building designers. The dimension for floor width was renamed to "floor (bay) width" for clarity. Additionally, a help button was added for each building dimension to outline dimension definitions visually (Figure 6.3.2).

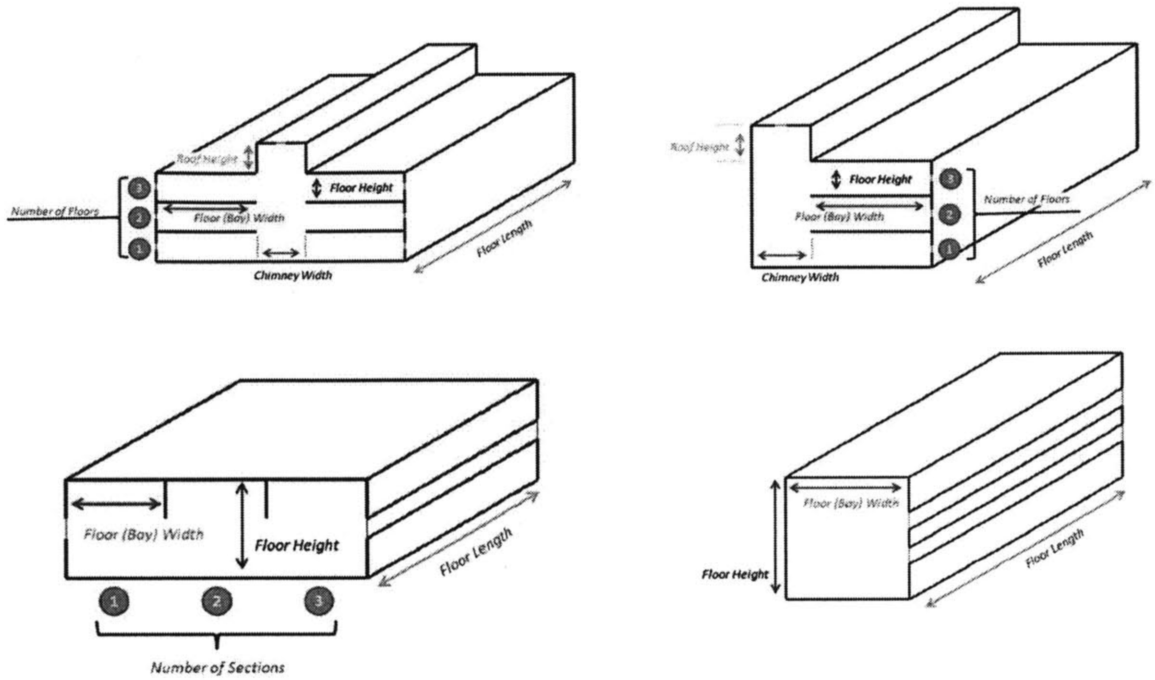


Figure 6.3.2: Visual Outline of Building Dimensions.

Window Dimensioning

In addition to building dimensioning, window dimensioning was also improved. The top window and side window specifications calculators were modified to allow for more intuitive window drawings and dimension naming conventions as well as tailored window dimension calculators for specific building types.

The top window specification calculator was modified to only be visible for the atrium-based building geometries (central atrium and chimney). The calculator features an architecturally inspired window diagram of the roof plan with a bold line outlining the entire window glazing area and a triangular section outlining the operable area of the window (i.e. the part of the window that a building occupant can open) (Figure 6.3.3). The calculator has inputs for the number of windows and the area of each operable window. With these inputs, it will calculate the "Top Window Area" and update its value on CoolVent's base interface.

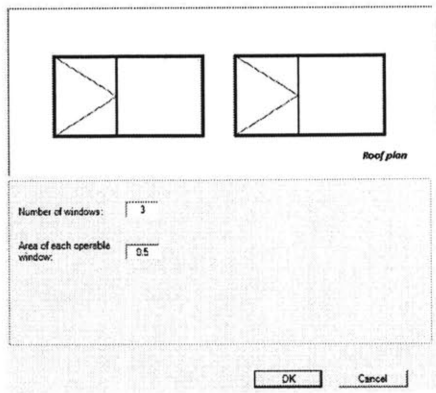


Figure 6.3.3: Top Window Specification Calculator for atrium-based building geometries.

Additionally, the top window specification calculator was renamed, "Roof Opening Calculator."

The side window specification calculator was also modified. For the atrium-based building geometries and the cross-ventilated building geometry, the side window calculator features a typical façade elevation diagram of the windows (Figure 6.3.4). The bold black line represents the overall window frame for glazing area considerations and the section of the window with a triangle marks the operable window area. The calculator has inputs for the total number of windows per façade per floor, the area of each operable window and the glazing area per window frame. When the "Ok" button is selected, the "Side Window Size" and "Side Glazing Area" parameters are updated on CoolVent's base interface window.

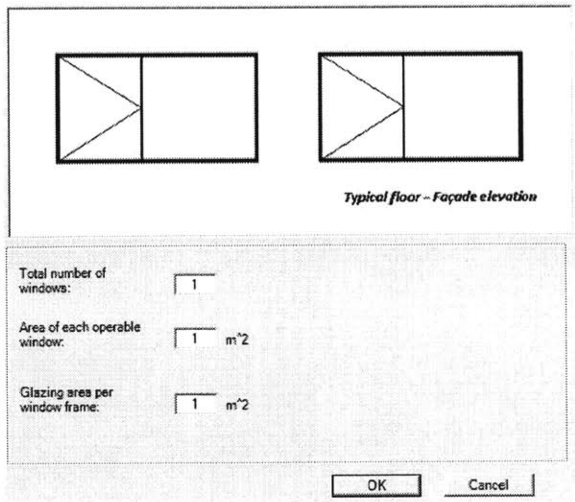


Figure 6.3.4: Side Window Specification Calculator for atrium-based building geometries and cross-ventilated building type.

For the single-sided building geometry, the side window calculator features a typical façade elevation diagram of the windows (Figure 6.3.5). The bold black line represents the overall window frame for glazing area considerations and the sections of the window with triangles mark the operable window areas (upper and lower) for the single-sided geometry. The distance of the center of the lower window to the bottom of the floor is represented by h_{low} and the distance between the center of the top and bottom windows is represented by ΔH. The calculator has inputs for the total number of windows per façade per floor, the area of each lower opening, the area for each upper opening and the glazing area per window frame. Additionally, there are inputs for the h_{low} and ΔH. When the "Ok" button is selected, the "Side Window Size" and "Side Glazing Area" parameters are updated on CoolVent's base interface window.

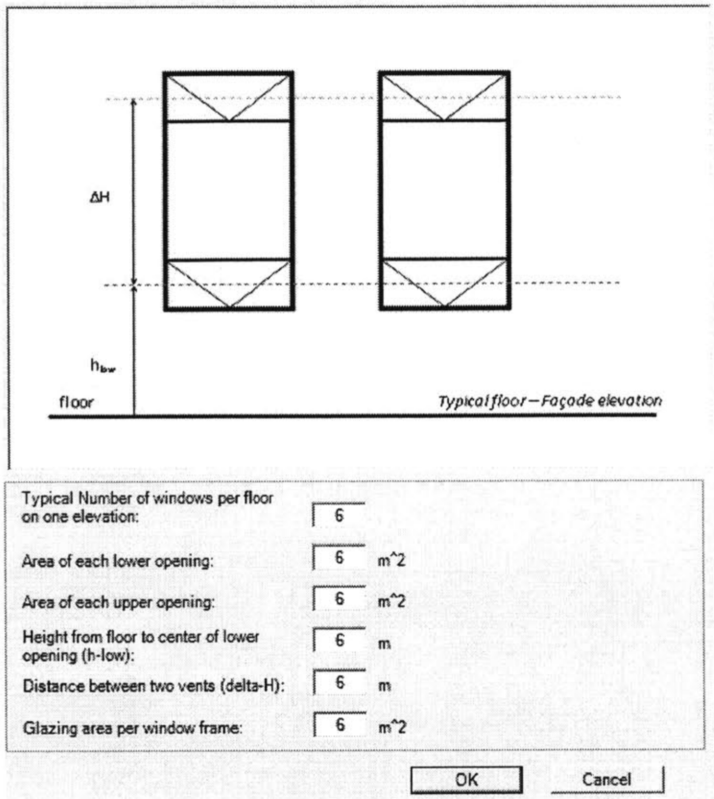


Figure 6.3.5: Side Window Specification Calculator for single-sided building geometry.

The side window specification calculators were renamed, “Side windows area calculator.”

All window calculators were re-implemented with input error checking. If any invalid inputs are entered into either calculator, a warning window will appear if the “OK” button is selected (Figure 6.3.6). The window warns users that their inputs are invalid and that their area and number inputs should be non-negative numbers.

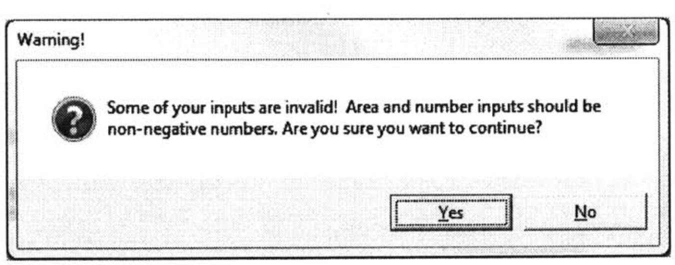


Figure 6.3.6: Window Calculator Invalid Inputs Warning Window.

Humidity Ratio versus Relative Humidity

While 68% of students found the selection of a custom thermal comfort model intuitive, only 53% of students felt they had intuition for defining comfort in terms of humidity ratio. This suggests that the minimum and maximum humidity ratio bounds for the custom thermal model selection on CoolVent's base would be more intuitive as a minimum and maximum relative humidity boundary. However, this change breaks correlation with the ASHRAE convention of defining humidity boundaries in terms of humidity ratio, so finding the optimal custom thermal comfort model input convention is left for future work.

Installation Instructions & Recommendations / Sample Outputs

Under the additional comments sections of the user study, several requests were made for improved installation instructions and recommended building geometries / sample geometries showing a "comfortable" or successful naturally ventilated building. In the future, these could both fit very nicely into a manual for the tool. The base data in the data text files for calculation could be deleted before a release to prevent false successful runs of the tool because Java Runtime is not installed. Sample building geometries and successful simulations could be downloaded with CoolVent and architects could load them into the software to gain familiarity with CoolVent.

7 Conclusion

CoolVent's base interface and visualization window have been modified to allow a more intuitive interface for architects in the early building design stages. Building dimension specifications and window specifications have been improved with new building dimensioning help windows and window geometries calculators. Input error prevention has been added to all parameters within the base interface. Finally, thermal comfort modeling (custom, ASHRAE and adaptive) has been added to CoolVent, allowing architects to understand how their design choices have not only affected the temperature and airflow in each of the zones of their building design but also how their design choices have affected the overall comfort throughout the zones of their building. From this, architects can now easily understand whether their building design can be successful as a naturally ventilated building and if not, they can use the provided interface to gain insight into how their design can be modified to make their building more sustainable.

7.1 Future Work

The main focus for future work should be: determining whether custom thermal comfort model humidity boundaries are more intuitive as humidity ratios or relative humidity inputs, changing air flow rates from CFM to m^3/s, developing more robust installation instructions and possibly writing both calculation and user interface code in Java, building up from a daily simulation to a yearly simulation and building a common window for the base interface, visualization and thermal comfort results sections.

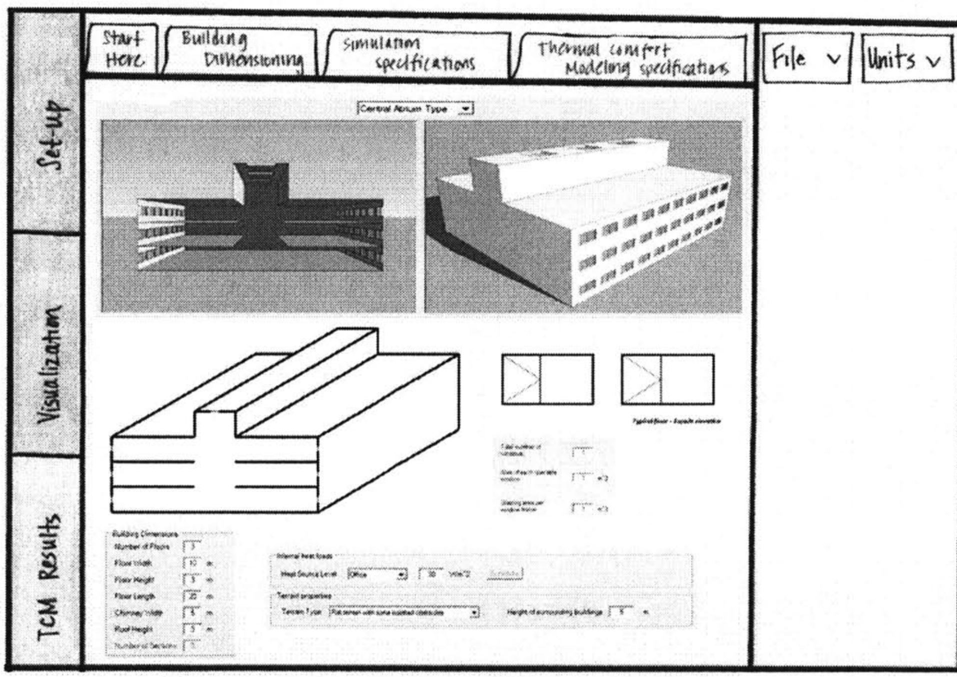


Figure 7.1.1: Future CoolVent Interface. A single window could allow architects to move between the current base interface, visualization window and thermal comfort results window. The new "Building Dimensioning" tab for the interface is shown. Under this tab, all building dimensions and geometry specifications will be made on a single tab.

In combining all the base interface and results windows into a single interface window, the interface could be designed with very similar tab structures (Figure 7.1.1). For the base interface, or "Set-up," the tabs could be simplified into "Start Here," "Building Dimensioning," "Simulation Specifications," and "Thermal Comfort Modeling Specifications." The "Start Here" tab would be very similar to the present version of the start tab. The "Building Dimensioning" tab could be designed to allow architects to input everything about their buildings' design. This includes selecting the building geometry to analyze, internal heat loading and building terrain type from the current "Main Inputs" tab as well as everything from the current "Building Dimensions" tab (Figure 7.1.1).

Similarly the "Simulation Specifications" tab could allow architects to specify whether they want to run a transient or steady state simulation, as well as all relevant weather data for their selected simulation type. Thermal mass specifications and window operation could also be defined under this tab. The "Thermal Comfort Modeling Specifications" tab could be very similar to the current Thermal Comfort Models tab; however, it could also allow users to select whether they want ASHRAE modeling to be based off of the 1.0clo or 0.5clo standard boundaries. There could also be a selection for whether they want to model adaptive comfort with 90% margins or 80% margins.

Beyond the base interface modifications, the visualization and thermal comfort results could be reorganized and expanded for yearly simulations. The animation drawing could be expanded to include average behavior across all months for the year or an architect could select in the "Settings" tab which months of the year are of interest to their simulation (Figure 7.1.2). The zone temperature plots could also be viewed as averages across each month on the "Building Zone Temp. Plots" tab.

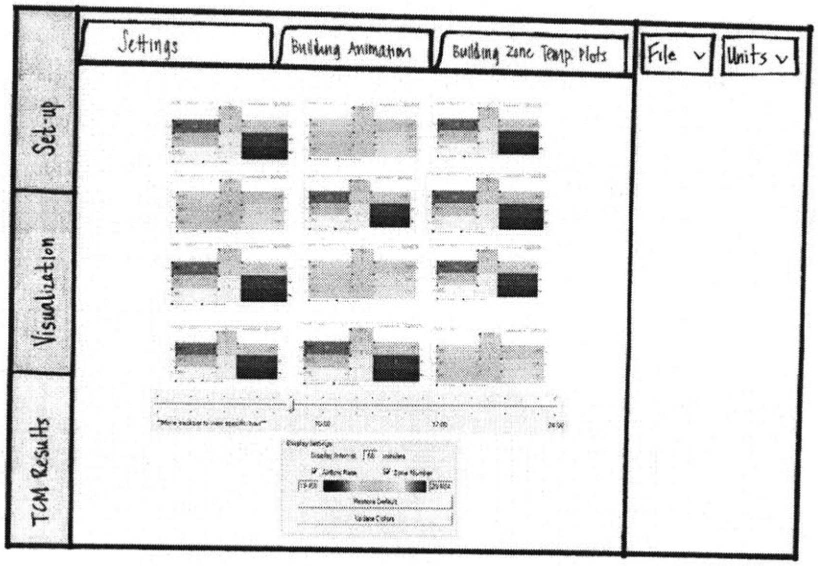


Figure 7.1.2: Future CoolVent Visualization Component. The visualizations could be modified to allow architects to view results of yearly simulations.

The thermal comfort results could be modified similarly to the animation drawings. For example, the building pie charts from the current thermal comfort models results window could be modified to show all months of the year the architect is interested in (Figure 7.1.3). The architect could then get a view of overall comfort for the year. Similar modifications could be applied to the zone temperature plots and the psychrometric charts.

Finally the side bar space under the file and units menus could be used to provide a constant summary of building selections. The calculate button could be placed in this side bar, along with buttons for exporting text files and specification calculators (such as building dimension and window geometry calculators). These modifications would minimize the multiple windows that CoolVent produces, increasing the fluidity of the interface.

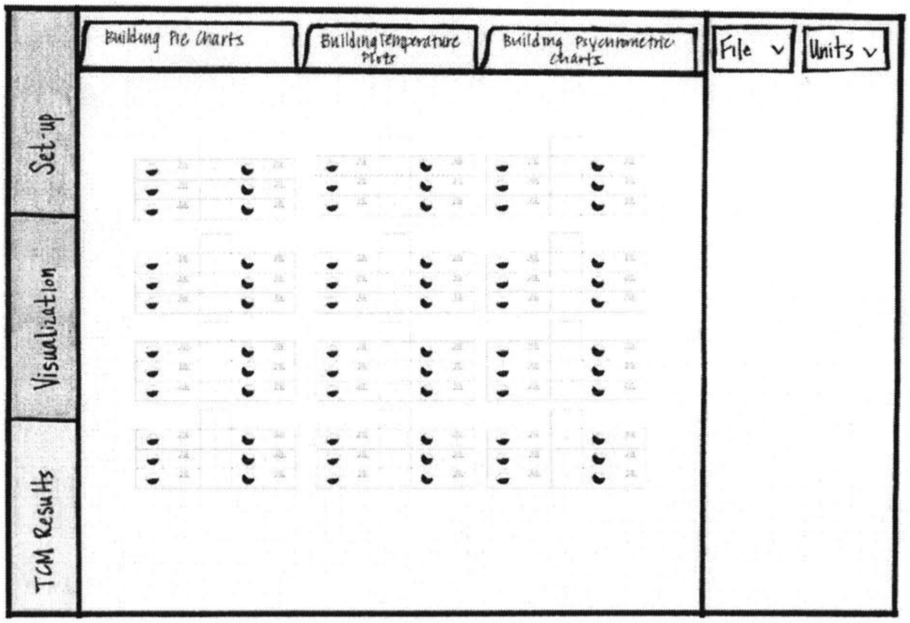


Figure 7.1.3: Future CoolVent Thermal Comfort Results Component. The thermal comfort results could be modified to allow architects to view results of yearly simulations.

Appendix A – Harvard GSD CoolVent Game

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6205 Simulation Game 2 – BUILDING SIMULATION GUIDELINES FOR COOLVENT

GENERAL GUIDELINES

Open Base >LOAD

- **ALWAYS START WITH the BASE CASE** Coolvent file.
- Right hand go to FILE>LOAD

Optimize your DESIGN

- **Follow the simulation instructions on the SUBMITTAL FORM.**
- Remember you can only change: Building Type, Orientation, Building Dimensions (shape and windows)
- Analyze results from previous simulations to understand how to optimize your current design.

Display Results

- **TO RUN A SIMULATION:** Calculate Inputs / Save Scenario > Visualize Results > View Results
- **DISPLAY BUILDING AND ZONE TOI's.** Overall building TOI and individual zone TOIs are reported in the "Temperature Pie Chart" tab
- **ANALYZE THE RESULTS:**. If you have overheated zones go to the "Temperature Graphs by Zone" tab to identify on how much are you overheating and determine the magnitude of the design change to be made
- **HUMIDITY CONCERNS:** go to the tab "Color Maps of Comfort by Zone" to identify humidity concerts for each zone. Black arrows represent hours were humidity may be too high.

BUILDING TYPE:

1- Open COOLVENT > LOAD Base Case File > Go to Main Inputs Tab.
2- Select Desired BUILDING TYPE. Remember you are not allowed to change anything else in this tab.

ORIENTATION:

1- Go to > Transient Inputs Tab.
2- Select desired MONTH to be simulated. Remember You should initially concentrate your analysis on the warmest month of the year since a ventilation strategy that is successful for that month is likely to also work during other months.
3- Select desired building orientation for that specific month.

BUILDING DIMENSIONS:

1- Go to > Building Dimensions Tab.
2- Input desired building dimensions for selected building type. **IMPORTANT**: you must overwrite inputs and not erase values before typing. If you erase values before typing the software will crash.
3- Be aware that dimension inputs vary by the building type you selected. For example, single-sided ventilation and cross-ventilation types do not allow you to input Number of Floors. For those building types just assume the number of floors you want for calculating the square footage of one floor.
4- When inputting window dimensions, Top Window Area and Side Window Size relate to operable window areas for each plane. Use a simple hand calculation to determine the operable window area in square meters from your WWR.
5- Side Glazing Area relates to the remaining fixed window area.
6- Internal Window Area is only available for Cross-Ventilation Building type. You are allowed a 100% of WWR (i.e. designing a completely open floor plan).

SIMULATION RESULTS:

1- Once you have selected the desired: building type, orientation and building dimensions you may simulate your design. To run the simulation click on "Calculate Inputs / Save Scenario" > Visualize Results > View Results.
2- To display the TOIs for the whole building and individual zones click on > Visualize Results > View Results. Overall building TOI and individual zone TOIs are reported in the "Temperature Pie Chart" tab.
3- The annual amount of overheating is measured through a metric called the Thermal Overheating Index (TOI). TOI is defined as the area weighted percentage of occupied hours per day during which a building is overheated. For example, a TOI of 50% can indicate that half of the floor area of a building is permanently overheated or that the whole building is overheated for half of the year.
4- If you have overheated zones go to the "Temperature Graphs by Zone" tab to identify on how much are you overheating and determine the magnitude of the design change to be made
5- To identify potential Humidity Concerns: go to the tab "Color Maps of Comfort by Zone" in the final results window. Black arrows represent hours were humidity may be too high.
6- Once you have a design that has no individual zones with TOIs above 20% for the warmest month you may run simulations for the rest of the months.
7- Write down the whole building TOI in the SUBMITTAL FORM for each month. Once you have the TOIs for all months (June, July, August and September) you will have to manually calculate the total average.

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BUILDING OPTIMIZATION GAME 2 – Natural Ventilation

Objective: The objective of this game is to design a naturally ventilated office building in Boston with a minimum amount of overheating using Coolvent. Details about the building are provided below. The annual amount of overheating is measured through a metric called the Thermal Overheating Index (TOI). TOI is defined as the area weighted percentage of occupied hours per day during which a building is overheated. For example, a TOI of 50% can indicate that half of the floor area of a building is permanently overheated or that the whole building is overheated for half of the year. (There are of course many other combinations that also lead to a TOI of 50%.)

Your goal is to get **the lowest possible annual TOI** for your building. Since Coolvent only reports monthly TOIs, you will have you estimate the annual TOI by repeating your simulations four times for the months of June, July, August and September and report the mean TOI for those four months. The GAME SUBMITTAL FORM will guide you through this process. (Tip: You should initially concentrate your analysis on the warmest month of the year since a ventilation strategy that is successful for that month is likely to also work during other months.) Good luck!

The Game: This is a timed exercise. You have 90 minutes and as many Coolvent simulations as your group can run. You may use multiple laptops per group. At the end of the 90 minutes, you have to submit your group's final design choices and TOI via the GAME SUBMITTAL FORM. For Assignment 5 - which is related to this exercise - we are asking you to document all simulations that you have run, what you learnt from the simulations and what logic you used to reduce your building's TOI. Again, your designs will be judged on simulated annual TOI only.

Strategy: For each Coolvent simulation, you will have to analyze the whole building TOI, hours of overheating for each building zone, monthly temperature profiles and the building's air-flow chart. Analyzing these charts will allow you to identify whether you have achieved thermal comfort within each space or where your remaining problem areas are. Overall building TOI and individual zone TOIs are reported in the "Temperature Pie Chart" tab. If you have overheated zones you can proceed to the "Temperature Graphs by Zone" tab to identify on how much you are overheating and determine the magnitude of the design change to be made. A brief set of Simulation Guidelines can be found below. **Important: We will only accept submittals for which the TOIs for all months have been simulated and the annual TOI has been determined!**

Building Description: Your task is to design an office building of brick and concrete construction located in Boston, MA, USA. The building floor area is 2800m^2 . The building has a high quality thermal envelope and is surrounded by 4 story-high buildings. The base variant has a Window-to-Wall-Ratio (WWR) of 40%. 5% of the window area are operable. The window Solar Heat Gain Coefficient (SHGC) is 0.6. Internal loads due to lighting, occupants and other equipment is 45W/m^2 during regular business hours and 9W/m^2 during non-business hours. The building has no exterior sun shading.

Table 1: Simulation rules: Your final design has to comply with the following boundary conditions.

SIMULATION RULES	
Description of building parameters you are able to alter to improve you building's TOI. You should always start your simulation using the "6205_SimGame2_Base.txt" file. You are not allowed to change any other simulation parameters in this file besides the ones described below.	
Parameter	Allowed Ranges
Building Massing	(a) single-sided, (b) cross ventilation, (c) chimney type, (d) central atrium
Building orientation	All available orientations
Building Dimensions	
Number of Floors	[1,..., 6]
Floor width	[6m,... , 30m]
Floor Height	[3m,... , 6m]
Floor Length	[10m,... , 50m]
Chimney width	[2m,... , 10m]
Roof height	[1m,... , 10m]
Window Dimensions	
Top window area (top operable windows)	< 30% of top surface
Side Window size (side operable windows)	< 20% of a single floor's façade (i.e. 20% WWR)
Side glazing area (fixed glazing)	< 80% of a single floor's façade (i.e. 80% WWR)

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BUILDING OPTIMIZATION GAME 2: Natural Ventilation

SUBMITTAL FORM

GROUP # ________

DESIGN VARIANT # __________

DESCRIPTION:

SIMULATION RULES

You should always start your simulation using the "6205_SimGame2_Base.txt" file. You are not allowed to change any other simulation parameters in this file besides the ones described bellow.

Parameter	Allowed values	Design values
Building Type		____ Single-sided ____ Cross ventilation ____ Chimney type ____ Central atrium
Building orientation		____ N, ____ NE, ____ E, ___ SE, ____ S, ____ SW, ____ W, ___ NW
Building Dimensions		
Number of Floors (#)	Min = 1 , Max = 6	____ Number of Floors (#)
Floor width (m)	Min = 6 , Max = 30	____ Floor width (m)
Floor Height (m)	Min = 3 , Max = 6	____ Floor Height (m)
Floor Length (m)	Min = 10 , Max = 50	____ Floor Length (m)
Chimney width (m)	Min = 2 , Max = 10	____ Chimney width (m)
Roof height (m)	Min = 1 , Max = 10	____ Roof height (m)
Window Dimensions		
Top window area (operable windows)	Max = 30% of top surface	____ Top window area (m2) (operable)
Side Window size (operable windows)	Max = 20% WWR	____ Side Window size (m2) (operable)
Side glazing area (fixed glazing)	Max = 80% WWR	____ Side glazing area (m2) (fixed)

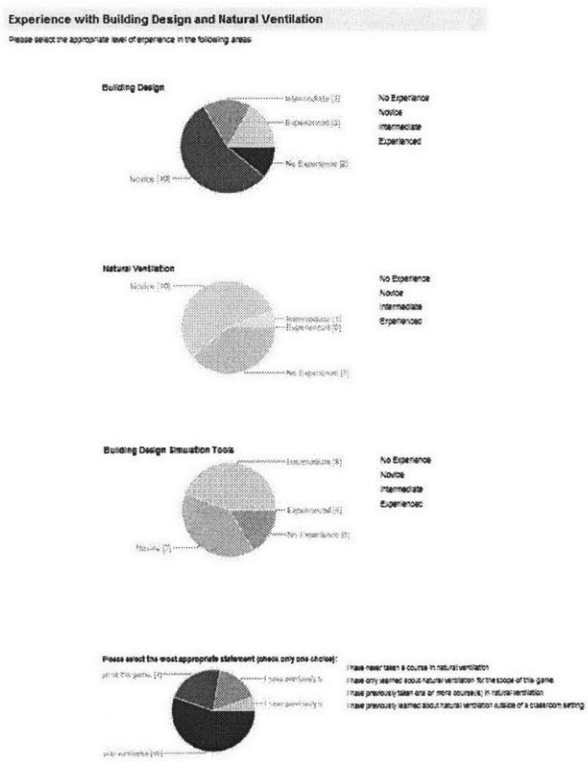
SIMULATION RESULTS

Your goal is to get the lowest possible annual TOI for your building. Since Coolvent only reports monthly TOIs, you will have you estimate the annual TOI by averaging the four monthly TOI's

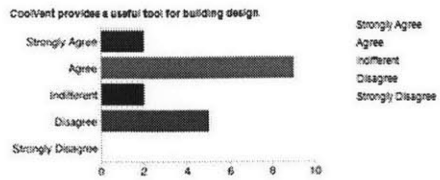
	Possible Humidity concerns	All individual zones with TOI < 20%	Thermal Overheating Index (TOI)
June	___ YES ___ NO	___ YES ___ NO	________ [%]
July	___ YES ___ NO	___ YES ___ NO	________ [%]
August	___ YES ___ NO	___ YES ___ NO	________ [%]
September	___ YES ___ NO	___ YES ___ NO	________ [%]
TOTAL BUILDING AVERAGED TOI			________ **[%]**

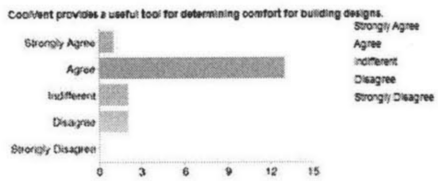
Appendix B – MIT Web-Based User Study

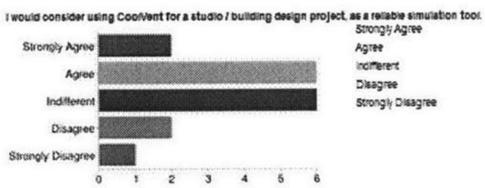
Experience

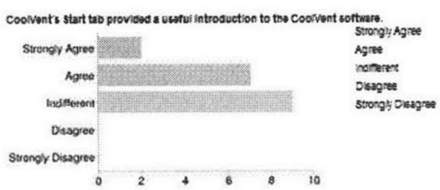


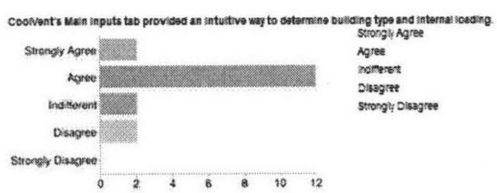
Overall Interface Experience



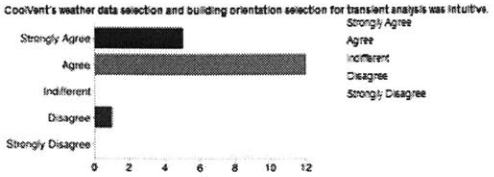




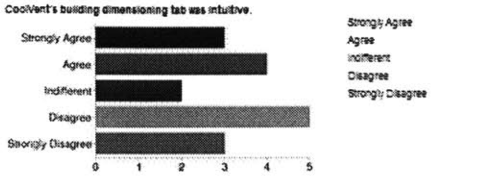




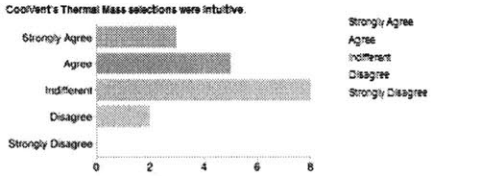
CoolVent's weather data selection and building orientation selection for transient analysis was intuitive.



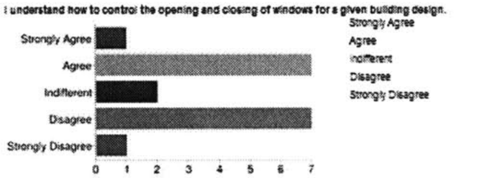
CoolVent's building dimensioning tab was intuitive.



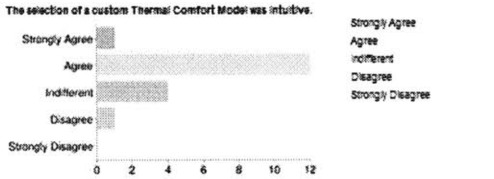
CoolVent's Thermal Mass selections were intuitive.



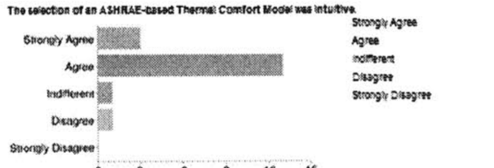
I understand how to control the opening and closing of windows for a given building design.



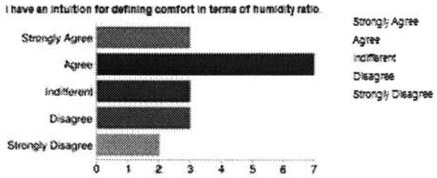
The selection of a custom Thermal Comfort Model was intuitive.



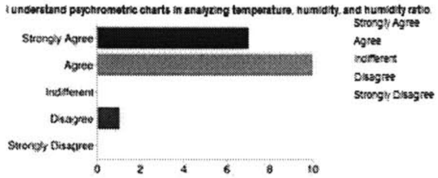
The selection of an ASHRAE-based Thermal Comfort Model was intuitive.



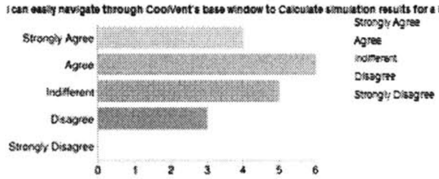
I have an intuition for defining comfort in terms of humidity ratio.



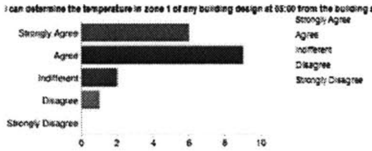
I understand psychrometric charts in analyzing temperature, humidity, and humidity ratio.



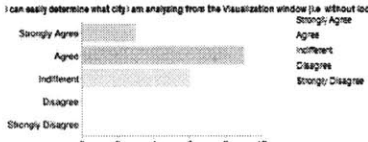
I can easily navigate through CoolVent's base window to Calculate simulation results for a building.



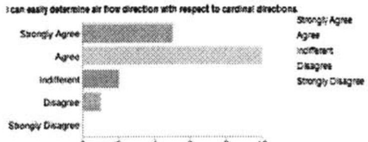
I can determine the temperature in zone 1 of any building design at 05:00 from the building animation (Visualization window).



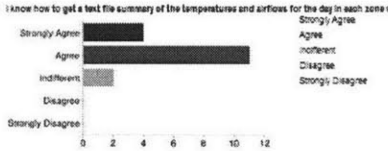
I can easily determine what city I am analyzing from the Visualization window (i.e. without looking back at the base interface window).



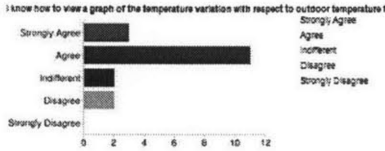
I can easily determine air flow direction with respect to cardinal directions.



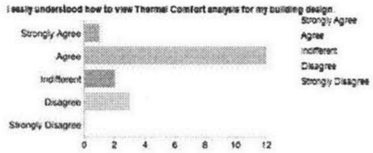
I know how to get a text file summary of the temperatures and airflows for the day in each zone of a building design.



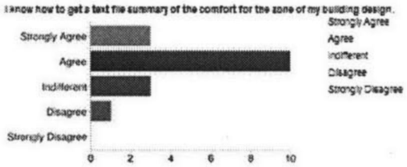
I know how to view a graph of the temperature variation with respect to outdoor temperature for each zone during the day



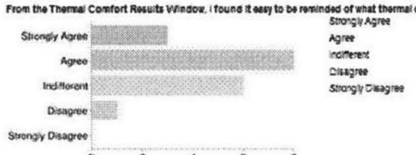
I easily understood how to view Thermal Comfort analysis for my building design.



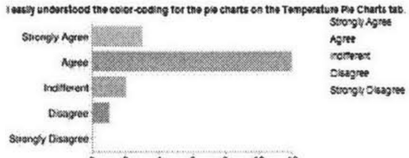
I know how to get a text file summary of the comfort for the zone of my building design.



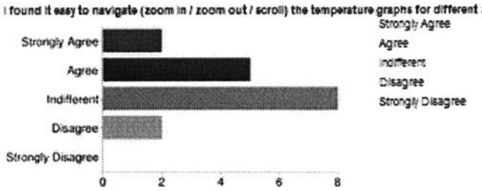
From the Thermal Comfort Results Window, I found it easy to be reminded of what thermal comfort model I was using to analyze my building (without having to look back at the main CoolVent interface window).



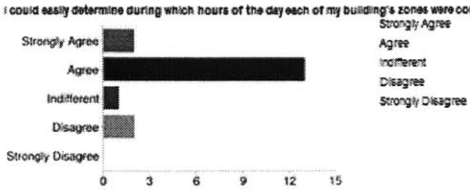
I easily understood the color-coding for the pie charts on the Temperature Pie Charts tab.



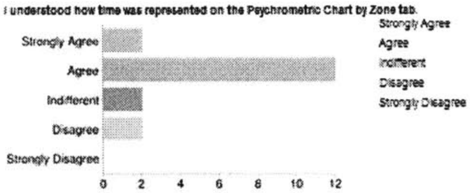
I found it easy to navigate (zoom in / zoom out / scroll) the temperature graphs for different zones on the Temperature Graphs by Zone tab.



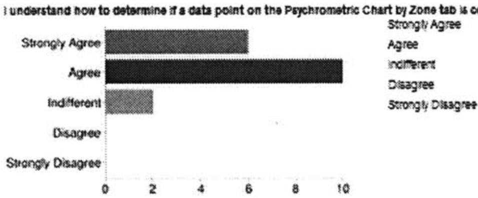
I could easily determine during which hours of the day each of my building's zones were comfortable, too hot or too cold from the Temperature Graphs by Zone tab.



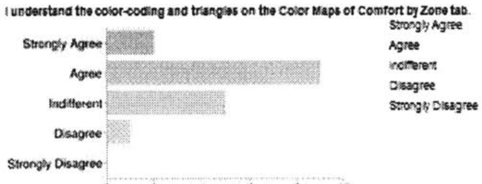
I understood how time was represented on the Psychrometric Chart by Zone tab.



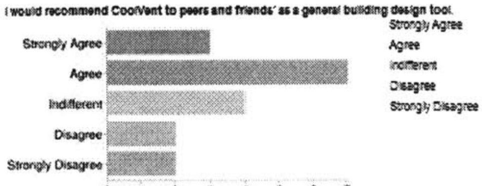
I understand how to determine if a data point on the Psychrometric Chart by Zone tab is considered comfortable.



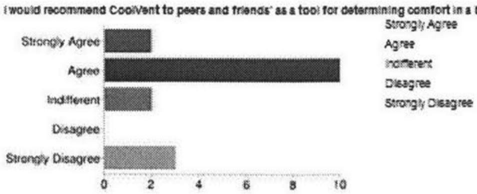
I understand the color-coding and triangles on the Color Maps of Comfort by Zone tab.



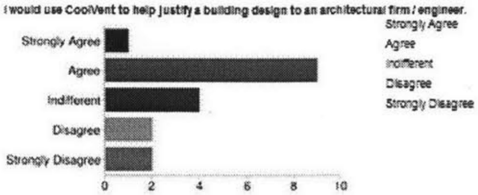
I would recommend CoolVent to peers and friends' as a general building design tool.



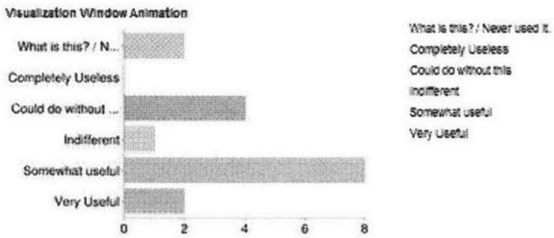
I would recommend CoolVent to peers and friends' as a tool for determining comfort in a building design.

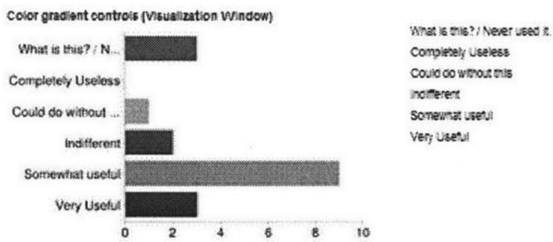


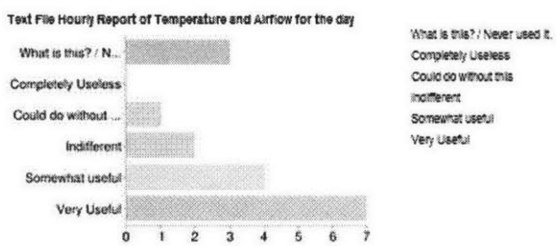
I would use CoolVent to help justify a building design to an architectural firm / engineer.

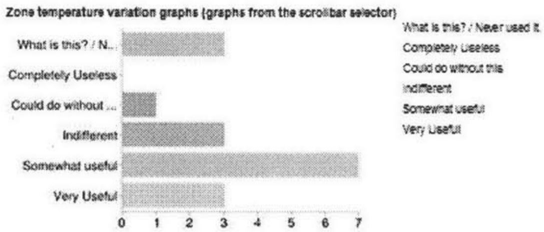


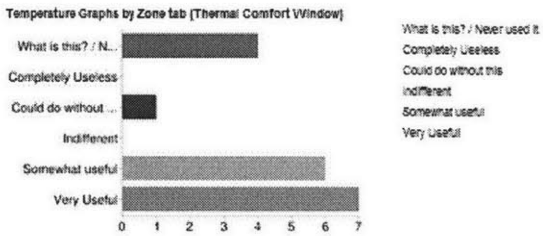
Component Usefulness

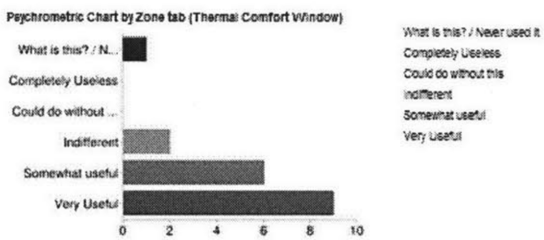




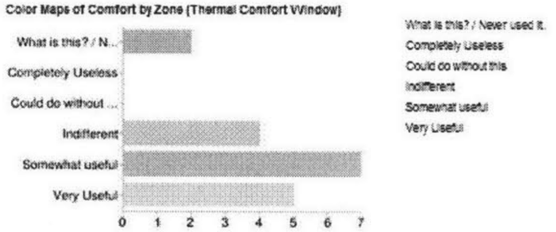



Zone temperature variation graphs (graphs from the scrollbar selector)
What is this? / N...
Completely Useless
Could do without ...
Indifferent
Somewhat useful
Very Useful
0 1 2 3 4 5 6 7
What is this? / Never used it
Completely Useless
Could do without this
Indifferent
Somewhat useful
Very Useful

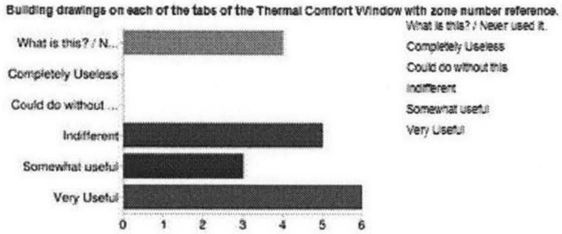

Temperature Graphs by Zone tab (Thermal Comfort Window)
What is this? / N...
Completely Useless
Could do without ...
Indifferent
Somewhat useful
Very Useful
0 1 2 3 4 5 6 7
What is this? / Never used it
Completely Useless
Could do without this
Indifferent
Somewhat useful
Very Useful


Psychrometric Chart by Zone tab (Thermal Comfort Window)
What is this? / N...
Completely Useless
Could do without ...
Indifferent
Somewhat useful
Very Useful
0 2 4 6 8 10
What is this? / Never used it
Completely Useless
Could do without this
Indifferent
Somewhat useful
Very Useful

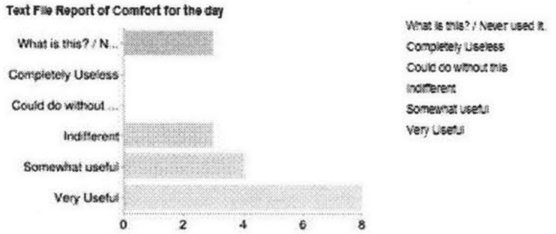
Color Maps of Comfort by Zone (Thermal Comfort Window)



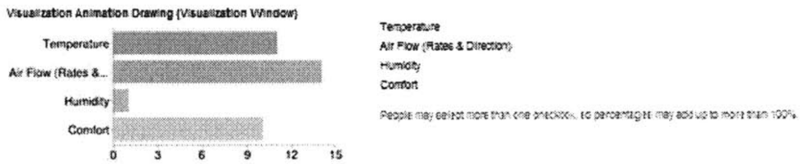
Building drawings on each of the tabs of the Thermal Comfort Window with zone number reference.

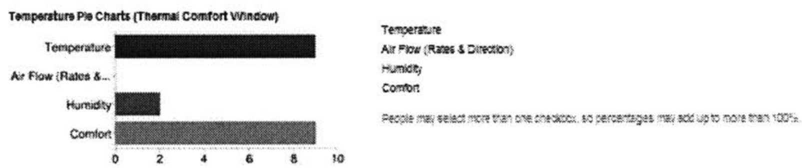


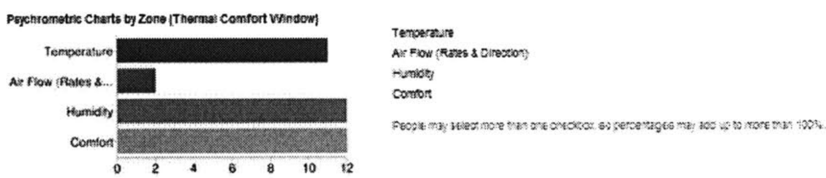
Text File Report of Comfort for the day

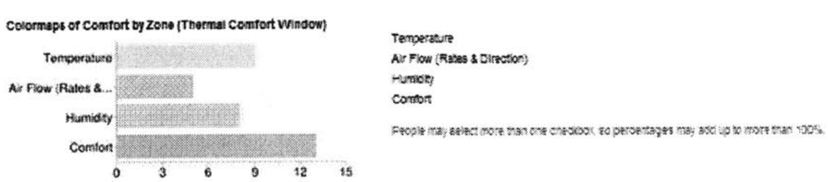


Understanding of Results









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